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THESIS

HUMAN FACTORS ENGINEERING AND OPERABILITY
IN THE DESIGN OF ELECTRONIC WARFARE SPACES
ABOARD UNITED STATES NAVAL COMBATANTS

by

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September 1985

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Human Factors Engineering and Operability in the Design of Electronic Warfare Spaces Aboard United States Naval Combatants

by

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Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING
(ELECTRONIC WARFARE)

ABSTRACT

The purpose of this thesis is to present and discuss a method of assessing the effectiveness of a work space layout. In addition, this method will provide the framework for pinpointing those areas of layout design where redesign will be most cost effective. The objective is to address inefficiencies in the layout of warfare modules on U.S. Navy combatants. In particular, the Electronic Warfare Module on aircraft carriers is assessed due to the highly time-critical nature of electronic warfare. The method chosen in this thesis is a modification of two techniques of assessment: Integration Analysis and Mission Operability Assessment Technique (MOAT). The portions of these techniques used are Link Analysis, Task Analysis, and Operability Analysis. The application herein concludes that the EW Module layout design on the latest NIMITZ-class aircraft carriers was less than 40% effective in promoting mission accomplishment.

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I. INTRODUCTION

A. BACKGROUND

As seen in several of the recent wars and conflicts, speed and timing are crucial in modern warfare. In the Falklands War, the lack of time available to react to a threat caused the loss of HMS SHEFFIELD. The HMS SHEFFIELD was sunk by fires that could not be brought under control as a result of a strike by an Exocet missile. Even though the ship had weapons systems that could have defeated the Exocet, its inability to initially detect the missile at a far range rendered these defenses useless. The Electronic Warfare (EW) operators on the SHEFFIELD had little warning of the Exocet due to self-induced jamming. When the self-jamming (inadvertent, of course) ceased, the Exocet was immediately detected, but it was too late to engage. The missile struck about ten seconds later. Although technologically superior, the British did not correctly manage the Radio Frequency (RF) spectrum and lost a ship. The self-jamming was caused by equipment interference and was either not noticed earlier or dismissed as unlikely to cause serious problems. This problem and others like it are now being resolved by the British.

In war at sea today, it is necessary to provide an adequate reaction time. Reaction time is the time between

detection of the incoming target and weapons engagement. Response time is the time between enemy weapons release and impact (i.e., the time available for detection, reaction, and engagement). In the example cited above, that adequate reaction time simply was not present. In the case of HMS SHEFFIELD, improper management of the electromagnetic (EM) spectrum set up the situation of inadequate reaction time. With the coming of sophisticated weapon systems and supersonic missiles, the amount of time available to respond to a threat has been steadily reduced. In World War II reaction time could be measured on the order of dozens of minutes. Today reaction times are on the order of dozens of seconds. With initial detection at the horizon, sea-skimming missiles offer only 30 seconds warning before impact. Today's Combat Information Center (CIC) needs to be organized in such a way as to derive maximum efficiency and speed from operations in order to reduce reaction time as much as possible.

The problem of reduced reaction time is not new and equipments in many areas has been developed to meet this need. The Navy Tactical Data System (NTDS) was developed to solve this problem. It reduces the amount of time needed to understand the tactical environment around the ship and by providing a more complete picture, aids sound decision making.

With the development and installation of effective defensive weapon systems onboard Navy ships, effort must now be devoted to the reduction of reaction time. Effective weapons are available, only the time to employ them correctly is needed. Effective long range sensor systems can provide adequate warning and "buy" time for the employment of the appropriate weapon. Therefore, it can be concluded that anything that "buys time" is of value.

But how does one buy time? There are two ways: (1) machines can be built to react more quickly or, (2) operators can be trained to respond faster. Although systems will help the Fleet sailor react quicker, there is a limit as to how fast he can respond. Working spaces need to be optimized so that the sailor can respond optimally. In this context, efficiency translates into speed which translates into reduced reaction time. The efficient arrangement of equipment in a working space has not been addressed by the Navy in such a way as to promote effective and efficient spaces. (For the remainder of this effort, the term "working space" or "work space" will be used to denote a combat space where data is searched for, collected, evaluated, disseminated, and/or acted upon.) An efficient and effectively laid out workspace will, intuitively, buy time. The barriers imposed by improper design and poor layout can never be totally compensated for by training.

B. NEED

During the procurement cycle, there is a requirement to perform human factors engineering on all new equipment to insure an adequate man-machine interface. However, there is inadequate methodology for insuring that space arrangement contributes to successful mission accomplishment. Space arrangement is, apparently, dictated primarily by the need to fit new and existing equipment into a space. This is not intended to belittle the efforts of those who are charged with designing the layouts and arrangements of combat spaces, but is intended to address methods for improving the efficiencies of layouts.

Before the layouts of combat spaces can be redesigned, it is first necessary to determine if there is a deficiency in the existing layout. A measure of adequacy of space arrangements must be developed. At present there is no such measure for combat systems layouts.

The field of human factors engineering has developed techniques for assessing the adequacy of tasks, subsystems, systems, and organizations. However, due to the dynamic nature of shipboard work space development there appears to have been few human factors engineering techniques addressing the arrangement of systems as applied to the space as a whole or the entire mission work areas. This is due to the fact that new equipment with new functions and

increased capabilities are constantly being introduced into spaces barely adequate for the original equipment.

As a result of the procurement cycle, human factors engineering is applied only on single systems or consoles. It has been recognized that training personnel to overcome the human factors design deficiencies is not cost effective in terms of either time, money, or manpower. The current requirement is for total individual system analysis in the areas of compatibility, interoperability, and human factors. It is mainly in the area of integrating these systems together in a work space that significant improvement is needed.

C. PURPOSE OF THESIS

The purpose of this thesis is to present and discuss a method of assessing the effectiveness of a work space layout. In addition, this method will provide the framework for pinpointing those areas where redesign will be most cost effective.

II. THE NATURE OF THE DIFFICULTY

A. CURRENT METHOD

How are space layouts currently assessed in the United States Navy? Or, perhaps, a better question is: is the current method of assessing space arrangements adequate? What is the current method?

There are two methods of improving a space layout. The first method is by fleet inputs. There are no formal procedures as such. To initiate a design change,a request for change (no specific format) is submitted by the individual (or ship) via his chain of command to the appropriate engineering office within the Naval Sea Systems Command (NAVSEASYSCOM). An engineer studies the proposal to see if it has merit. If it does, he forwards it within NAVSEASYSCOM and through the appropriate system command. From this point, if it is acceptable, it is forwarded to the Office of the Chief of Naval Operations (OPNAV). OPNAV is the configuration manager for all platforms and makes the final decision on configuration or layout design changes. For example, during the Board of Inspection and Survey (BIS) Acceptance Trials for USS CARL VINSON (CVN-70), a strong case for redesigning the CIC arrangement was made by the commissioning crew. In particular, the cramped space of the EW Module on CARL VINSON was addressed and a solution

proposed. That solution apparently was forwarded to NAVSEASYSCOM and Space Naval Warfare Command and then to OPNAV because it has been incorporated in the layout of the EW Module on CVN-71 (See Figure 1).

The other method in improving space design is a mock-up approach. At various organizations, mock-ups are used to test the layout designs considered. These organizations are under contract to produce a specific kind of mock-up. The Naval Ocean Systems Center (NOSC) in San Diego does some mock-up work under the direction of NAVSEASYSCOM. At present they have a carrier Combat Information Center (CIC) mock-up. It contains the Display and Decision portion which includes the Surface Warfare Module and the Air Warfare Module. It does not contain Detection and Tracking, the Electronic Warfare Module, or the Anti-Submarine Warfare Module.

B. DEFICIENCIES

The current method of improving the layout/arrangement design of some of the spaces on our surface ships, has four major shortcomings: (1) lack of user input, (2) lack of human factors engineering, (3) lack of a learning curve, and (4) no planning for growth. These deficiencies and the impact they have on the effectiveness of the space is now discussed.

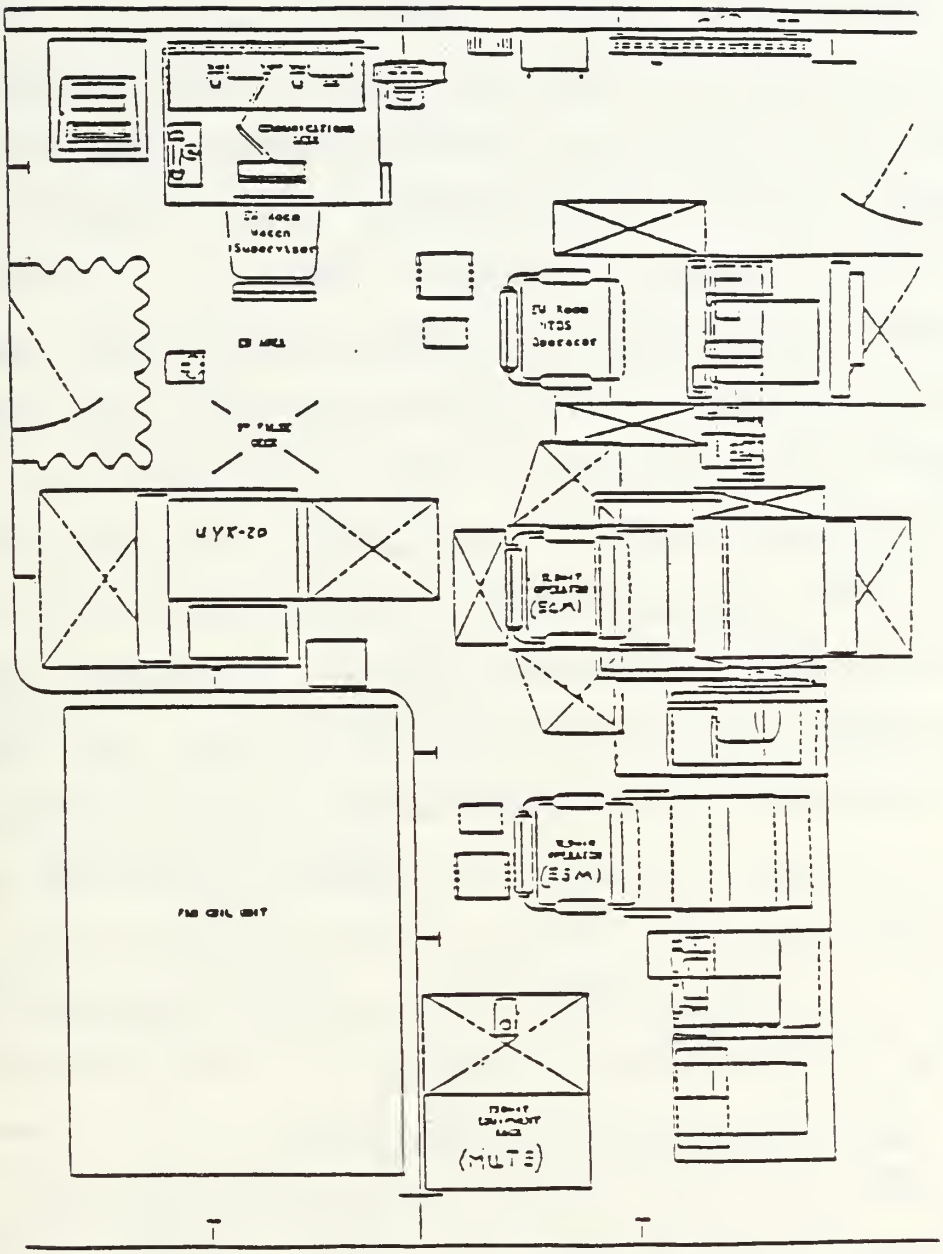


Figure 1. EW Module Layout (Proposed)

1. Lack of User Input

The current method of layout improvement has little or no operator/user input. There is, perhaps, some user input as in the CARL VINSON CIC example cited above but this appears to be the exception rather than the rule. There is no formal method of submitting a design change through normal Navy channels to NAVSEA. This is a very serious deficiency because sketchy or total lack of fleet input is counter-productive. The design of a space by those who do not and will not be using it has a tendency to result in a far from optimal design. For example, a radio or "bitch box" that is frequently used is placed just out of reach. In the EW Module on USS CARL VINSON, the 12 MC (internal communications set) used to communicate with the Tactical Action Officer (TAO) and INTEL(among others) is placed such that the EW Supervisor and NTDS operator have to get up out of his seat to talk. There is, in fairness, a hand mike that can be attached but this has the undesirable side effect of cluttering the workstation.

2. Lack of Human Factors Engineering

The only human factors engineering being employed is basic. This method has been characterized as "moving the furniture around". This is done until there is an apparently workable solution. Again there is inadequate fleet or operator inputs to check the "new" arrangement. It must be said that those employing this method are trying to

find an arrangement that facilitates an efficient and effective operation. This method is the best method currently available to accomplish this task, but still something is lacking.

3. Lack of a Learning Curve

However good the results of the mock-up method may be, there is no apparent learning curve in successive layouts. For example, the EW Module layout on USS AMERICA provided the necessary room for the activities of EW and gave the impression of smooth efficiency and competence. However, on later aircraft carriers (most notably, the NIMITZ class) the EW Module arrangement is a regression and in nowise approaches the room and layout effectiveness found on AMERICA. If the NIMITZ class carrier EW Module layout was intended to be an improvement over AMERICA, it failed.

4. No plan for Growth

The current method is deficient in terms of its potential for growth. Few designs provide room for expansion for either new equipment or modifications to older equipment. When new equipment is added, the space for it must come from someplace, even if that area has another function. Simply adding new equipment does not aid the operation of the overall work area and may even be counterproductive in that efficiency may be reduced.

When lead units are designed and built, they are constructed with only existing equipment is mind (this is a

general rule and there are some exceptions). There is some small amount of room for expansion of capabilities but it is thought that the new equipment will replace older equipment and take up the same amount (or less) of room and fit into the same space. This thought does not take into account new missions for the space with corresponding new equipment, new capabilities, and new space requirements. Therefore, one can readily see that new equipment must be added wherever there is room for it. Sometimes the space where the new equipment is added is unsatisfactory for the equipment and its operation. By way of example, USS CARL VINSON is a NIMITZ class aircraft carrier and was built using essentially the same blueprints as the lead ship. The EW Module space was not changed even though the SLQ-17 and SSQ-82 (MUTE), not yet procured when NIMITZ was designed and built, were slated for CARL VINSON (and all carriers, eventually)(See Figure 2). Only one equipment rack was removed to make way for both equipments. The SLQ-17 console fits into the vacated equipment rack. This still left the computer unit (about one and a half racks) and MUTE (which was designed and built wider than the standard rack) to be placed somewhere within the EW Module. The SLQ-17 computer rack was placed against the bulkhead in the middle of the space. At most, three operators could fit comfortably into the EW Module even though General Quarters manning calls for four operators, and MUTE was placed outside the EW Module in

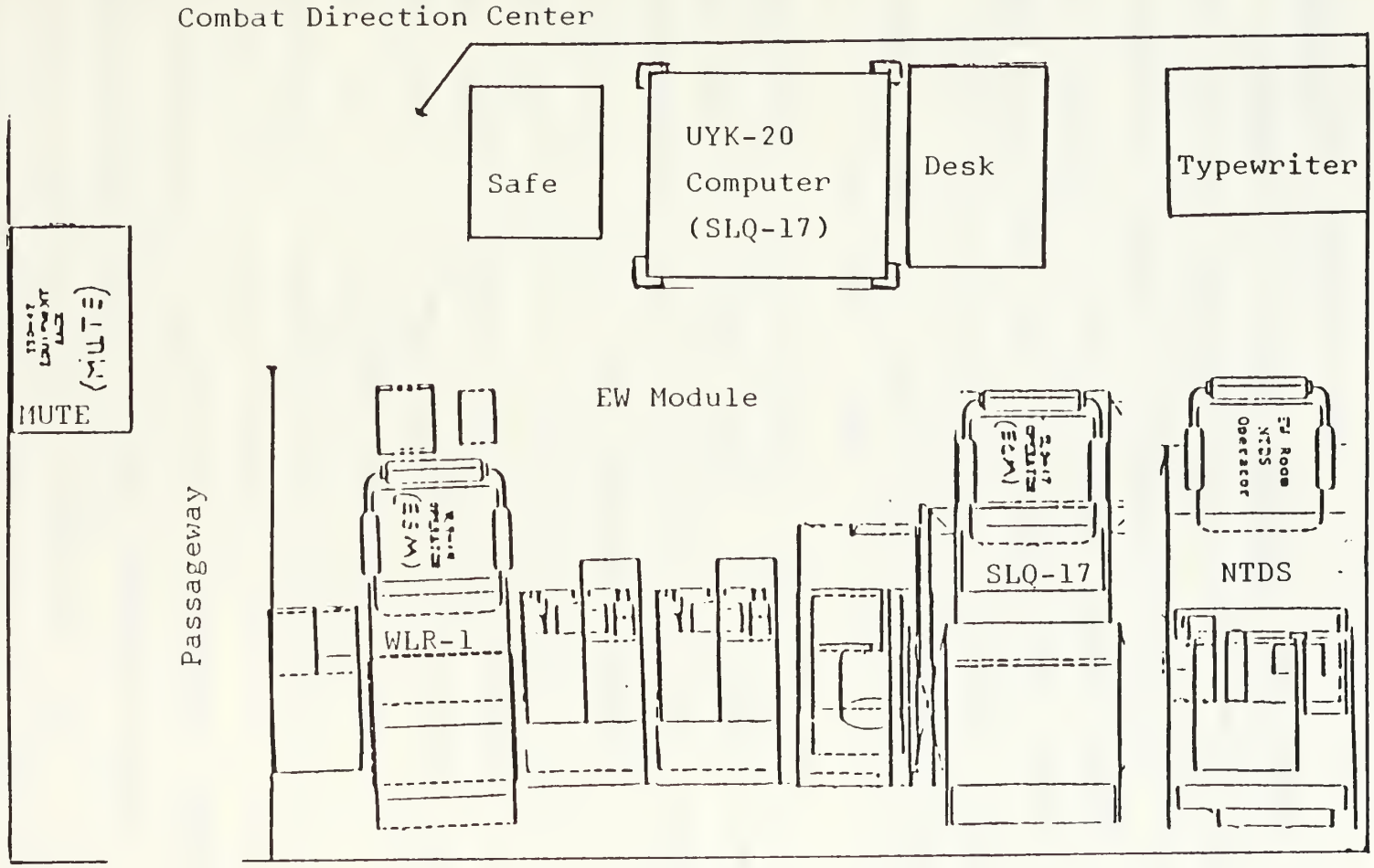


Figure 2. USS CARL VINSON EW Module

a passageway within CIC that was heavily traveled. There was simply no room in the EW Module for both the EW operators and MUTE--one or the other had to go.

In addition to the problems cited above, to accommodate the inclusion of all the equipment in the EW Module, some severe space economies had to be made. The layout now took on the appearance as shown in Figure 2. To allow some passage of operators and maintenance people among and around the equipment, a "straight line" layout was adopted. This had the sole advantage of allowing all the equipment possible to be place in the space. However, the question can logically be asked, "Does such an arrangement add or detract from the efficiency and effectiveness of space utilization in accomplishing the mission?" New equipment added to a space that was not designed for it may cause integration problems due to its intrinsic nature (i.e., in the equipment itself), its new location (e.g., the SLQ-17 computer rack), and reduced workspace (in our example, several racks where one used to be to the exclusion of another piece of equipment--MUTE).

The remainder of this thesis will be given over to attempting to find a workable solution to the problem of adequately designing a work space, in particular, an EW Module. As indicated earlier this is an area where the costs are in dollars and effort, but the payoff is in shorter reaction time and, ultimately, in ships and lives saved.

III. APPROACH

A. IMPROVEMENT TO LAYOUTS

The solution to layout/arrangement improvement is neither simple nor straightforward. An improvement, however, can be found in a threefold approach to the problem. These are: (1) a ship class, module, mock-up at a land based laboratory, (2) fleet inputs added to it on a regular basis, and (3) a quantifiable measure that can be used to determine overall effectiveness and pinpoint problem areas.

Establishing a class, module, mock-up at a land based laboratory makes good sense. Here, the results of several mock-ups can be stored and compared. Here, too, a "learning curve" can be established. What does not work for one class and module may never work, or it may work for another class ship and another module. The cost of mock-ups can be kept low. Mock-ups of new equipment entering the fleet can be sent to just one location and then incorporated into the design or redesign. Mock-ups of new ship classes can easily be done there.

NOSC at San Diego seems to be a good place to have this mock-up facility for several reasons. First, experts there have already done some mock-up work and have a certain amount of experience in this area. Secondly, they are near

a good source of fleet inputs in San Diego. Once a mock-up was designed (or redesigned), NOSC could request some fleet operators from one of the ships of that particular class and these operators could critique the mock-up and make suggestions for improvement. For added realism and additional inputs, a mock scenario could be played out by the operators on the mock-up. This has the added possible benefit of uncovering any oversight by either NOSC or the operators' critique. The two logical places for the mock-up site are Norfolk, Va. and San Diego, Ca.

Fleet inputs in the design/redesign of the layout process is of the utmost importance. The fleet operators are the people who have to use the equipment and accomplish the mission within the space. They, from the benefit of several years individual and many years collective experience, will be able to note problems with the mock-up that the designers may have missed. Designers of single equipments tend to think of their equipment in isolation from all others. Layout designers are often not familiar with the operating characteristics of all the equipment. Fleet operators suffer from neither of these deficiencies. However, operators do have a bias toward doing things as they are currently done and may resist change. Nevertheless, they are still probably the best ones to evaluate the mock-up.

As seemingly complete as the combination of both laboratory mock-up and fleet input might be, there is one more area that needs to be covered. This is a quantitative assessment of the present layout and mock-up layouts. There are several reasons for this. First, a quantitative assessment of a present layout may indicate that it does not need improving or that the cost of improving the layout is not justified by the amount of improvement. Second, a quantitative assessment based in part on questionnaires to fleet operators may awaken thoughts of some inadequacy that was not present in the conscious memory but was tucked away in the recesses of the mind. Finally, a quantitative assessment is necessary to be able to compare functional layouts one to another. The final aspect of this approach is a way of assessing the effectiveness of the layout.

Various techniques have been developed that will aid in assessing effectiveness. However, these methods have been used on systems that are dissimilar to those found on ships and must be modified. The method that will be utilized is a combination of three different but related techniques: Task Analysis, Link Analysis, and Operability Analysis. Two major studies have been reviewed to determine the extent of these analyses and how they might be modified for a layout improvement application. These are Integration Analysis and Mission Operability Assessment Technique (MOAT). A brief

look at each of these will indicate the salient portions of each for this application.

Integration Analysis is the integration of Task Analysis, Operator Interviews, and Link Analysis to evaluate a system's Functional Mock-up. Integration Analysis was designed as a viable Test and Evaluation technique for the earlier stages of Developmental Test and Evaluation (DT&E) in order to reduce design discrepancies and minimize acquistion costs and time [Ref. 1].

MOAT, an evaluation methodology, measures the operability of a system or subsystem in terms of operator tasks performed during a mission. It essentially is an Operability Analysis.

> In general, MOAT addresses the problem of how well an operator can use a system or subsystem to perform tasks within the mission context. Contrasted to evaluations using human engineering design criteria which present only pass or fail information, this technique provides information on the degree of system and/or subsystem success or failure.[Ref. 2:pp. 3-4]

The underlying techniques of task analysis, scaling methodology, and multi-attribute utility (MAU) theory have been integrated into one comprehensive methodology.

> MOAT systematically structures operator tasks in accordance with mission needs and then assesses the operability of these tasks through conjoint measurement. All assessments are then integrated within rules established through MAU theory. The output of MOAT is quantitative information about the operability of an entire system, such as a fighter or attack aircraft; the operability of specific subsystems such as radar, communications, or navigation, and; finally, the operability of each task performed during a mission phase. In short, MOAT measures subsystem and/or system goal attainment.[Ref. 2:p. 4]

Having briefly described both Integration Analysis and MOAT, parts of each were combined in this thesis to provide a technique that is well suited to a layout improvement application. From MOAT the techniques to assess man-system compatibility (i.e., Task Analysis and Operability Analysis) were used. This was considered in a larger context in order to assess man as a team rather than as an individual. Operability Analysis consists of two parts: multi-attribute utility (MAU) theory (to be discussed later), and scaling theory. The use of questionnaires and Link Analysis came from Integration Analysis. Note that both Integration Analysis and MOAT contain Task Analysis. The questionnaires serve two purposes. First, they focus attention on the problem areas of the design/arrangement. Secondly, the completed questionnaires support assessment of the layout effectiveness. Finally, the questionnaires form a link between the various analyses and operator inputs.

MOAT was designed to assess man-system compatibility. The original MOAT used a construct that embodied the three most important divisions of the man-system compatibility--man, system, and mission and how all three interact during mission accomplishment. The difference considered here lies in the evaluation of a team of operators rather than just one man and the fact that a group of subsystems arranged in a particular manner is used to determine the operability. Hence, the three most important divisions of the man-system

compatibility are now the team, system, and mission. As can be easily seen, the basic premise of MOAT is unchanged in that the man-system compatibility is still being evaluated. In short, is the arrangement of equipment in a space "user friendly"? Note that even though an arrangement of equipment within a work space is being specifically addressed, man-system compatibility subsumes the equipment arrangement within the work space. The basic contention is that the best operators and best subsystems in a poorly designed space may be less effective than operators with less ability and a less capable system that is in a space that is well designed for mission accomplishment.

MOAT uses the term operability to reflect how the man, system, and mission interact during mission accomplishment.

> By definition, operability reflects (1) the amount of effort required by the operator in task accomplishment, (2) the degree of subsystem technical effectiveness in aiding the operator in task accomplishment, and (3) how important the task is for mission success.[Ref. 2:p. 19]

This can be redefined slightly to indicate (1) the amount of effort required by the operators (team) in task accomplishment (task difficulty), (2) the degree that equipment arrangement aids the operators (team) in task accomplishment (arrangement effectiveness), and (3) how important the task is for mission success (task criticality).

B. TASK ANALYSIS

The purpose for Task Analysis is to determine those tasks and subtasks needed to successfully perform the mission of the Module. Without specifying the tasks performed within the EW Module, it would be difficult, if not imposaible, to determine layout effectiveness. task/subtask identification forms the basis of both the Link Analysis that is discussed later and the MOAT technique of Operability Analysis. Each task and subtask that operators perform will be examined and fit into the larger picture of module mission. The effort within the EW Module can be shown to be divided hierarchically: Module mission, operator tasks, and operator subtasks. This hierarchy is divided in the following manner: the aggregate of the subtasks comprises the individual task and the aggregate of the individual tasks comprises the mission.

The mission of the EW Module is to conduct Electronic Warfare which includes Electronic Warfare Support Measures (ESM) and Electronic Warfare Counter-Measures (ECM). This entails attempting to deny any potential enemy the exploitation of the electromagnetic spectrum while preserving it for our own use. The EW Supervisor (EWS) is responsible for providing timely evaluated EW information, EW data, and EW control (to the rest of the battle group when so designated as EW Control Ship). This is accomplished by three operators and three work stations (WLR-1, SLQ-17,

and NTDS). The tasks and subtasks that are performed within the workspace are listed in Table 1. While the module mission delineates the overall responsibility for the module, the operator tasks are the first major subdivision. These are the tasks that each operator must accomplish at his workstation in order to contribute to mission accomplishment. The operator subtask is a further division of the operator tasks. These aggregate together for ESM/ECM. These are listed in Table 1 and were drawn from various sources and confirmed by the EW Module personnel. Each workstation and, therefore, each operator has a piece of the "puzzle" and only by putting them together can any sense be made out of the parts. In this case, as so many others, the whole will be greater than the sum of the parts.

Note in Table 1 that there are actually five positions listed: EW Supervisor, WLR-1 operator, SLQ-17 operator, NTDS operator, and Status Board keeper. During normal steaming conditions, one of the three position operators is also the EW Supervisor and, therefore, he has a dual role to play. Additionally, there is no Status Board keeper during normal steaming watches. During Condition One, General Quarters, the Module is manned with five people. Therefore, the Task Analysis considered the more complicated situation of General Quarters.

TABLE 1. OPERATOR TASKS AND SUBTASKS

EW Supervisor

Task: 1.1 Direct ESM search
Subtasks
1.1.1 Assign search parameters to SLQ-17
1.1.2 Assign search parameters to WLR-1
1.1.3 Assign ESM sensor report responsibilities -- own ship
1.1.4 Assign ESM sensor report responsibilities -- force
1.1.5 Initiate manual ID request - ship
1.1.6 Initiate manual ID request - force
1.1.7 Monitor automatic correlations/associations, (SLQ-17)

Task: 1.2 Report/Disseminate EW Information
Subtasks
1.2.1 Report evaluated EW information
1.2.2 Provide EW recommendations
1.2.3 Update status board near NTDS console
1.2.4 Brief/debrief embarked Airwings
1.2.5 Navigation by passive EW

Task: 1.3 Counter Hostile Environment
Subtasks
1.3.1 Promulgation of ECM employment criteria

NTDS Operator

Task: 2.1 Collect and enter EW data into NTDS
Subtasks
2.1.1 Enter manual ID information into NTDS
2.1.2 Enter manual ESM/NTDS track associations
2.1.3 Perform triangulation of ESM bearing lines
2.1.4 Enter EW fixes
2.1.5 Advise operators of bearing resolution
2.1.6 Evaluate externally reported ESM bearings

Task: 2.2 Report/Disseminate EW Information
Subtask
2.2.1 Report evaluated EW information
2.2.2 Update status board near console

SLQ-17 Operator

Task: 3.1 Conduct ESM Search
Subtask
3.1.1 Monitor automatic correlations/associations
3.1.2 Establish operating modes of SLQ-17 (ESM)
3.1.3 Enter detection and response parameters (ESM/ECM)
3.1.4 Monitor environment on NTDS console
3.1.5 Evaluate displayed data

TABLE 1. OPERATOR TASKS AND SUBTASKS (continued)

Task: 3.2 Report/Disseminate EW Information
Subtask
3.2.1 Report evaluated EW information
3.2.2 Provide ESM/ECM data to NTDS
3.2.3 Monitor entry of EW data into NTDS
3.2.4 Update status board

Task: 3.3 Counter Hostile Environment
Subtask
3.3.1 Engage targets with ECM
3.3.2 Establish ECM operating Modes
3.3.3 Assist in promulgation of ECM employment criteria

WLR-1 Operator

Task: 4.1 Conduct ESM Search
Subtasks
4.1.1 Search assigned bands
4.1.2 Analyze intercepted signals
4.1.3 Check intercepts for images/harmonics
4.1.4 Accurately DF intercepted signals
4.1.5 Assist in evaluating ECM

Task: 4.2 Report/Disseminate EW Information
Subtasks
4.2.1 Provide ESM data to NTDS
4.2.2 Report evaluated EW information
4.2.3 Update status board near position
4.2.4 Log all intercepts

Task: 4.3 EMCON
Subtasks
4.3.1 Monitor EMCON
4.3.2 Report violations of EMCON
4.3.3 Log violations of EMCON
4.3.4 Monitor MUTE

EW Status Board

Task: 5.1 Maintain Status Boards
Subtasks
5.1.1 Communicate with operators
5.1.2 Advise operators of any information received
5.1.3 Update status boards

C. LINK ANALYSIS

Link Analysis is a technique that will provide the information needed to produce an acceptable arrangement of men and machines in a system [Ref. 3:p. 204]. The idea is that the "best arrangement" can be found only by optimizing different types of links that are important in the particular system being designed. By way of definition, a link is a connection between (a) an operator and a machine or (b) two operators [Ref. 3:p. 204]. These links may be visual (such as an instrument scan), functional or manual (hand to control), or verbal (communications). Inefficiencies are present when links are comparatively long, crossing one another, blocked, or outside optimal visual or reach envelopes. The links are produced from the task analysis and illustrate all the operator-required functional, visual, and communication tasks. Link Analysis can be applied to all scenarios involved during all operational and emergency conditions [Ref. 3:p. 205 and Ref.4]. Link Analyses are normally of two types: panel layout and tactical compartment or multiple operator work area. With the development and procurement of individual subsystems (i.e., WLR-1, SLQ-17, etc.) a certain amount of panel layout link analysis has been done. However, little if any has been done on the combination of systems arranged in a workspace (in this example, the EW Module). Hence, the

Link Analysis will necessarily be of the latter type (i.e., multiple operator work area).

The multiple operator work area type of link analysis is dependent on the correlation matrix. Beginning with the correlation matrix and an area layout, all interactions (links) required to perform a particular functional task are examined in terms of the frequency with which they occur and their criticality. If the criticality is assigned a numerical value, it may be multiplied by the frequency in order to obtain a weighted link value. The work area is overlaid with the weighted links permitting a picture of all the interactions taking place within the system being analyzed. The system design can then be modified to shorten the distance between the workstations that are connected by the weighted links [Ref. 5].

Figure 3 contains the correlation matrix for the EW Module in CARL VINSON. A correlation matrix is a figure that provides an indication of the links between two operators, positions, or between an operator and a position. Usually a criticality associated with the particular links is included in the matrix. In Figure 3, only the links of interest are listed. The figure is read by selecting the two entries for which links are desired and reading diagonally down from the top one and diagonally up from the bottom one until the intersecting diamond is reached. The diamond contains both the particular links between the two

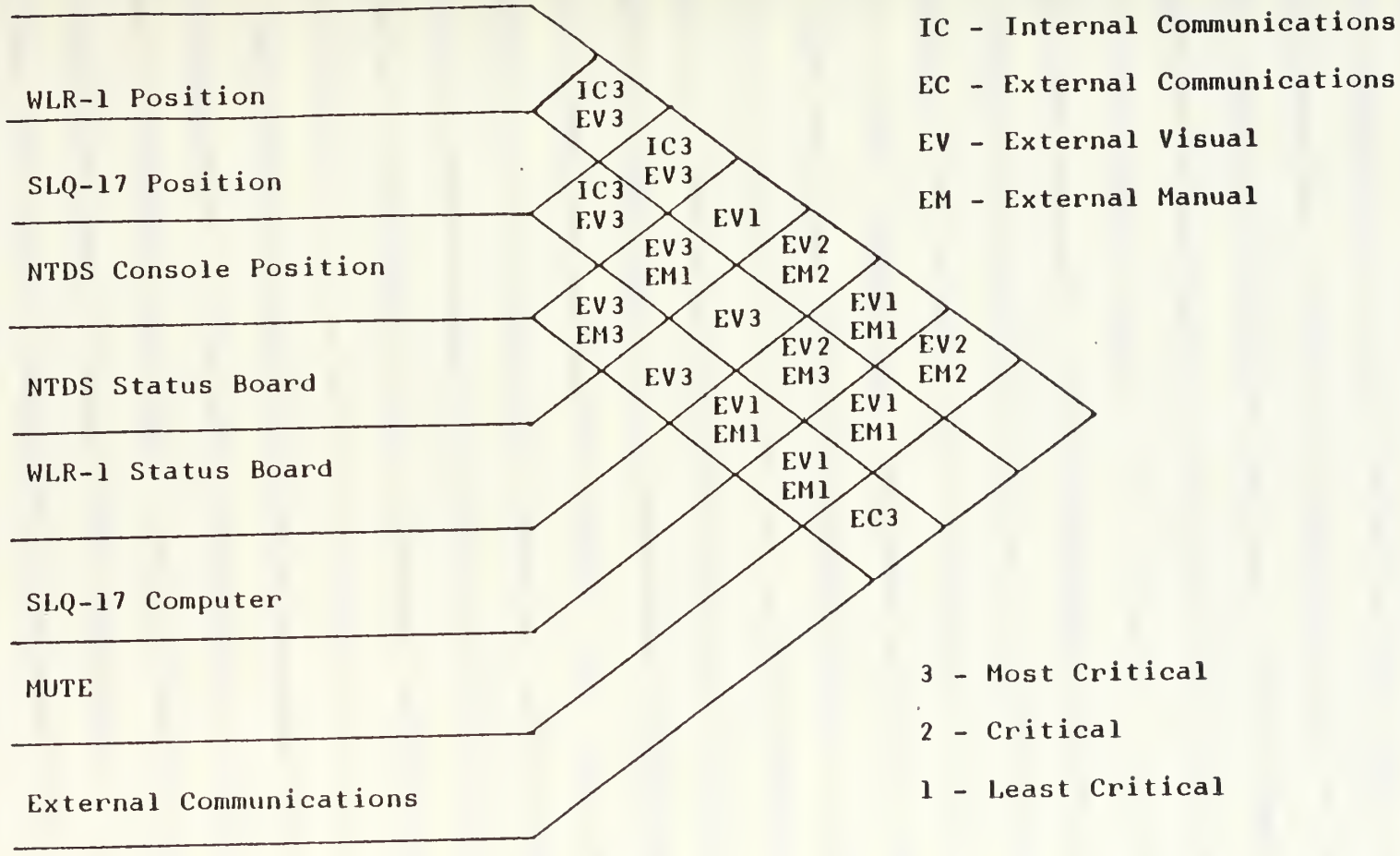


Figure 3. Link Correlation Matrix

entries and the criticality of those links. The notation along the right side of the figure indicates what links are between each component of the module. A separate notation provides an indication of the criticality of that particular link: most critical, critical, and least critical. The most critical link is one that is absolutely essential to accomplish the mission. A critical link is one that prevents severe degradation in the accomplishment of the mission and the least critical link has a small impact. It remains only to multiply the links by a frequency of operation to obtain a Weighted Link Value. The Weighted Link Value will be obtained from the results of the Link Analysis Questionnaire.

The type of links are communication, visual, and manual. The communication links are further subdivided into internal and external. The internal communication links are the voice interaction between operators while the external communication links are those voice and/or electronic links with other modules, persons, and/or platforms. The visual links can also be divided into internal and external. The internal are concerned solely with those links between the operator and his equipment or console. The external are those between the operator and other consoles and/or equipment. Similarly, the manual links, internal and external, are between the operator and his equipment or console and the operator and other equipment and/or

consoles, respectively. Since we have already considered that link analysis may have been done on individual systems and our concern is for the multiple operator work area, we will not be concerned with the internal visual and internal manual links. This leaves just four links analyses to be done; the internal and external communications, the external visual, and external manual links.

When the internal communication links are considered, it is noted that there are links between the EW Supervisor and both the WLR-1 and the SLQ-17 operators to promulgate orders. Next, there are links back to the EW Supervisor when one or the other have found either the signal of interest or something else that may be of interest. There are also links between the WLR-1 operator and the SLQ-17 operator. This last may be queries for information about their particular equipment set up or the passing of information to directing the other's search. The links between all three may be in the form of equipment status or failure. The internal communication links are shown in Figure 4.

The external communications involve primarily the EW Supervisor with any of the following: TAO, INTEL (the Intelligence center), SURFACE, AIR, Trackers, ASW (Anti-Submarine Warfare) Module, SSES (Ships Signal Exploitation Space), FLAG, FWC (Force Weapons Coordinator), or SWC (Ship's Weapons Coordinator).

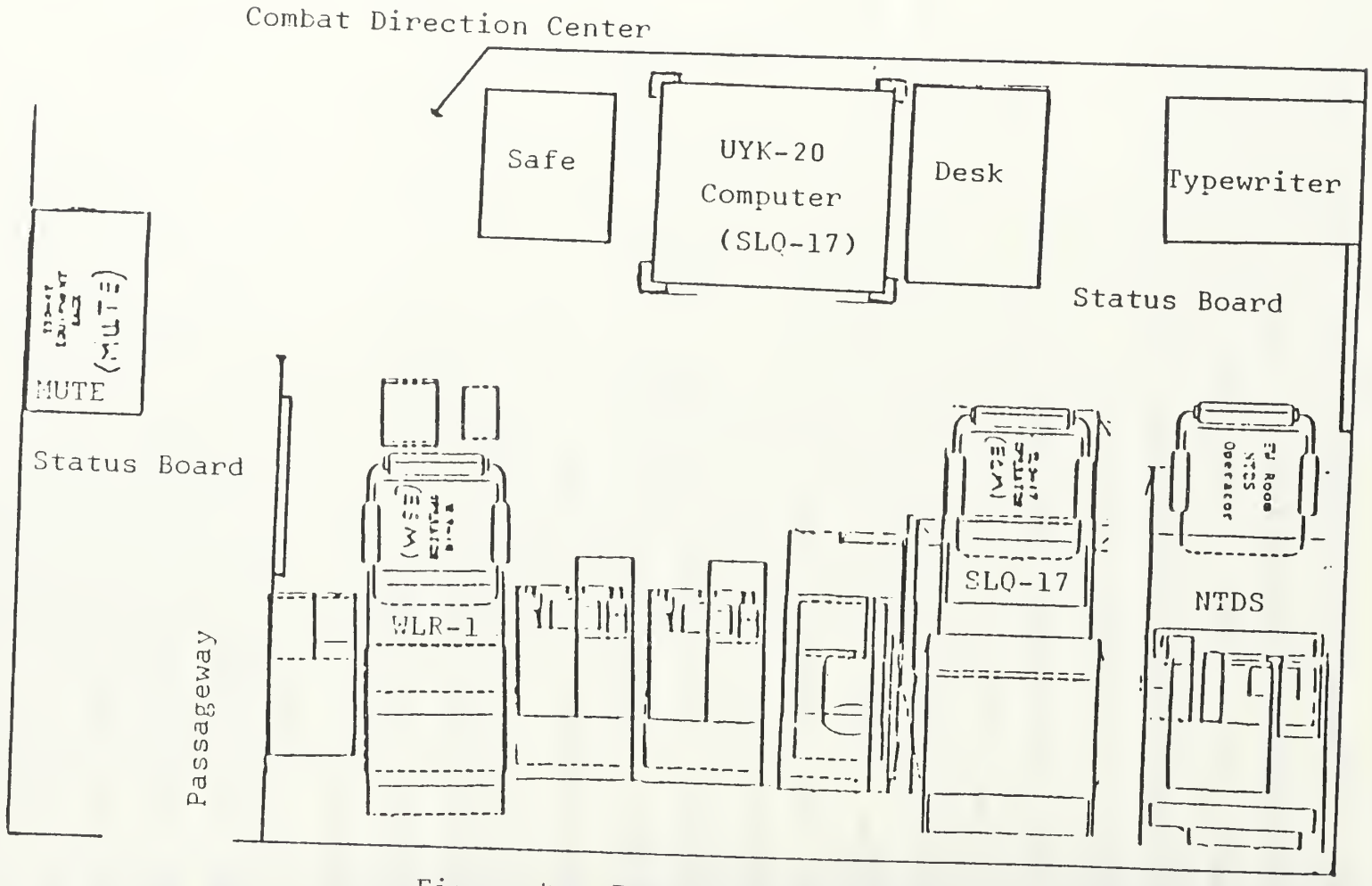


Figure 4. Internal Communications Links

The external visual links involve all of the operators viewing the status boards and each other's workstation. These external visual links are important for the additional information they provide to the operator. The visual reference to the other workstation builds an internal working model of the environment within the operator's mind thus enabling him to more quickly fit new data into the tactical picture and anticipate subsequent events. Without this interaction, effective Electronic Warfare control can not be attained.

Figures 5 and 6 show the external visual links. Figure 5 shows visual links between operators and Figure 6 indicates visual links between the operators and the status boards (there are only two status boards that can be clearly seen).

The final link that will be considered is the external manual link. Although there is no requirement for an operator to control more than one workstation, there are some external manual links that must be addressed. For example, all those equipments that are part of the EW Module for which there is no manning authorized will fall under this category. The AN/SSQ-82 MUTE is a prime example. MUTE is a monitor device that requires no manning and only cursory glances to ensure that it is functioning correctly. When adjustment is needed due to Force or ship EMCON changes, an external manual link for one of the operators takes place. Another example is the SLQ-17 UYK-20 computer.

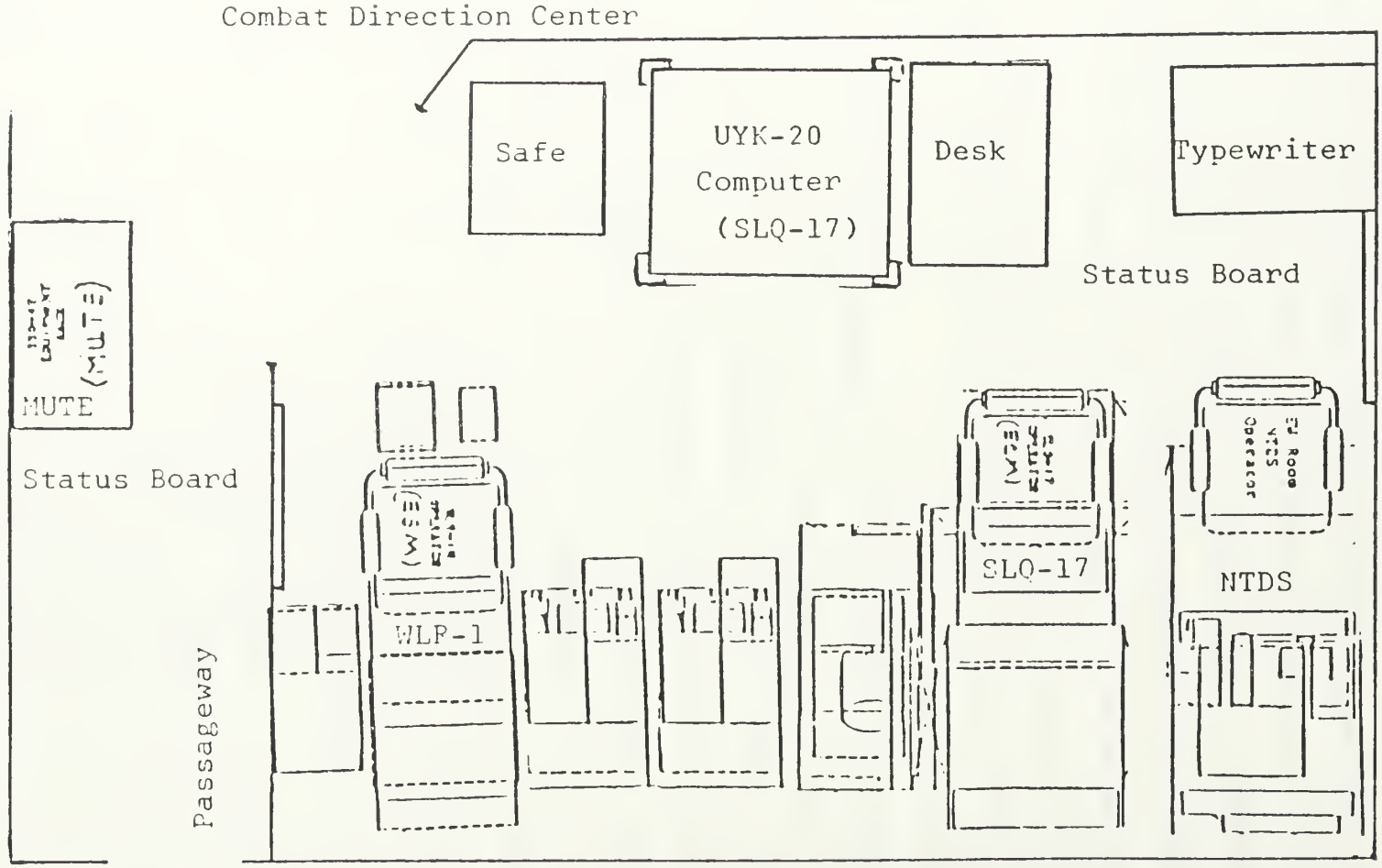


Figure 5. External Visual Links - Operators

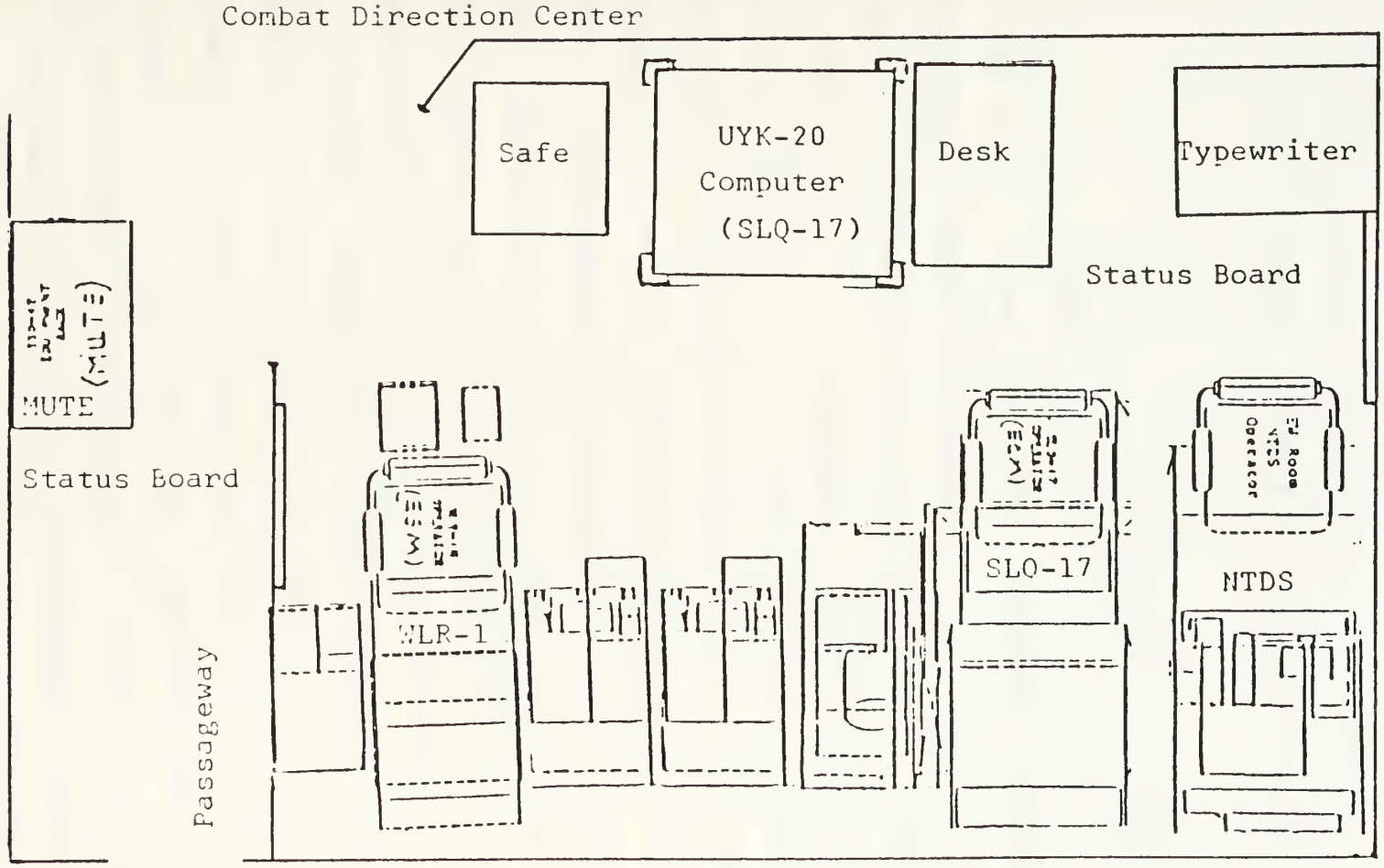


Figure 6. External Visual Links - Status Boards

This equipment is not adjacent to the SLQ-17 and one of the operators (normally the SLQ-17 operator) may need to reload, reboot, or reconfigure the system in the event of a casualty or normal operations. Figure 7 shows the external manual links.

D. OPERABILITY ANALYSIS

In the introduction to this section, it was stated that Operability Analysis was comprised of MAU and scaling theory. MAU is a Bayesian-oriented decision-making paradigm. There are three major aspects of the MAU model which are particularly important to this application. First, the basic structure principle in MAU is hierarchical decomposition. The mission is broken down into hierarchical grouping of tasks and subtasks. The model provides the structure and rules necessary to investigate and integrate the interrelationships of all these tasks and subtasks. Second, the definition of utility used in the MAU model allows for the optimum evaluation of alternatives which is dependent upon the selection of a single criterion. This means that multidimensional outcomes must be transformed into a single figure of merit such as utility, system worth, system effectiveness, or, as in this application, operability. Third, a scaling of the selected criterion. The scaling methodology used in this application, as in MOAT, was conjoint measurement.

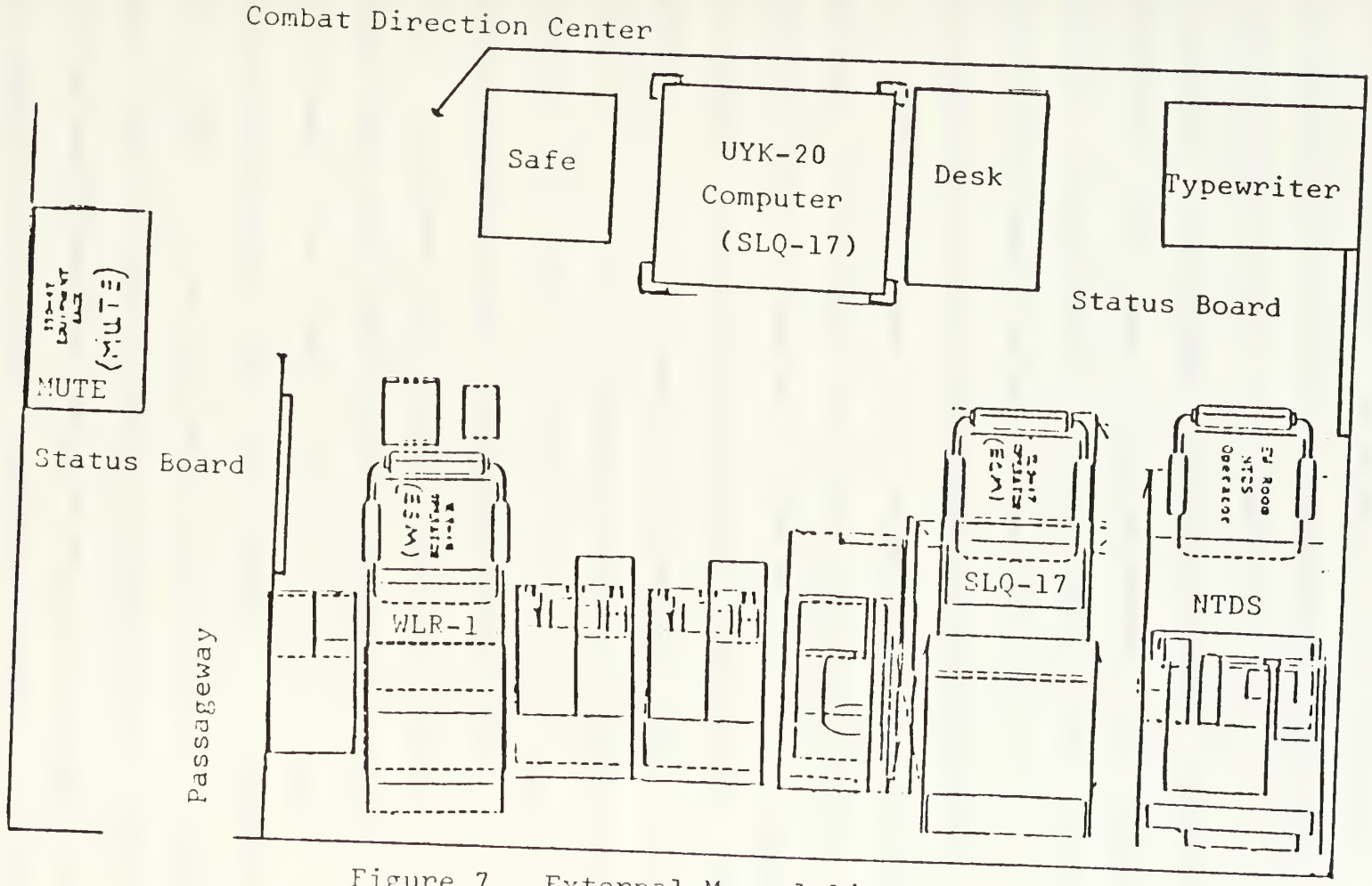


Figure 7. External Manual Links

Recall that operability can be viewed as a function of task criticality, operator workload, and space effectiveness. Therefore, when considering each task from a operability standpoint, each task that is performed has some combination of these three dimensions. There is a difficulty in assessing the degree of each attribute and combining them into a meaningful measure of operability. Since this can not be assessed directly by objective methods, the scaling methodology of conjoint measurement was devised to assess space operability subjectively. The problem of scaling tasks in dimensions of criticality, frequency, and system effectiveness has been successfully solved by using objectively anchored rating scales [Ref. 2:p. 20]. Therefore, a similar rating scale procedure seemed suitable in this instance.

The major difficulties involved with this approach are those of measuring the degree of operator effort (or watch section effort) and the layout effectiveness. This was to be expected, however, since not only were these different from any known previous study but also involved interactions on a higher scale than that experienced before. There is a substantial correlation in rating of task difficulty and subsystem effectiveness. The attempt to solve the rating scale problem is accomplished by dividing it into two separate ratings. On the F/A-18 program it was desirable to have two ratings; one with respect to pilot

workload (PW) and one with respect to the technical effectiveness (TE) of the subsystem [Ref. 2:p. 20]. A similar approach is attempted here with operator workload (OW) (it is assumed that this can be directly translated into watch section workload) and space effectiveness (SE). This application of Operability Analysis is concerned with assessing the task criticality, the operator workload, and the space effectiveness of a module layout. All are values on an ordinal scale. Two of these, space effectiveness and operator workload, need to be upgraded, through some methodology, to an interval scale in order to aggregate them over all tasks to achieve an overall measure of Module operability. To this end, conjoint measurement and its associated scaling procedures seemed suitable for a transformation to the desired unidimensional interval level scale. It is here that the delta method was employed. What conjoint measurement and the delta method do is allow separate rating of OW and SE (despite their mutual dependency) to be obtained and be combined in such a manner that a one-dimensional scale, having interval properties, is created. This scale might just as well be called the combined OW-SE scale. Rating on this scale can then be plugged into the MAU model. An assessment of the effectiveness of the EW Module layout with respect to a certain subtask can be determined. Aggregated together,

these will provide an indication of the overall effectiveness of the layout upon mission accomplishment.

E. QUESTIONNAIRES

Link Analysis, Task Analysis, and Operability Analysis will be completed by a series of two questionnaires. The first questionnaire (the Link Analysis Questionnaire) was targetted at Link Analysis and provided the frequency component for a completed Link Analysis. The second questionnaire (the Operator Subtask Questionnaire) confirmed the Task Analysis that went into building it and also provided the raw data needed to perform the Operability Analysis. From the Operability Analysis came the assessment of the Total Module Operability (TMO).

The questionnaires, as shown in Appendix A, were designed to do two things. First, the Link Analysis Questionnaire gave a general idea of the type and degree of deficiencies in the space in terms of link deficiencies. Second, it focused the operators' attention on the arrangement of the work space and any deficiencies that were there. It was hoped that the questions brought into sharp relief the difficulties for which the operator unconsciously compensates during the mission. By highlighting these deficiencies through the Link Analysis series of questions, the detailing of them in the Operator Subtask Questionnaires, hopefully, provided good human engineering

data with which to evaluate the Module Operability of the EW Module.

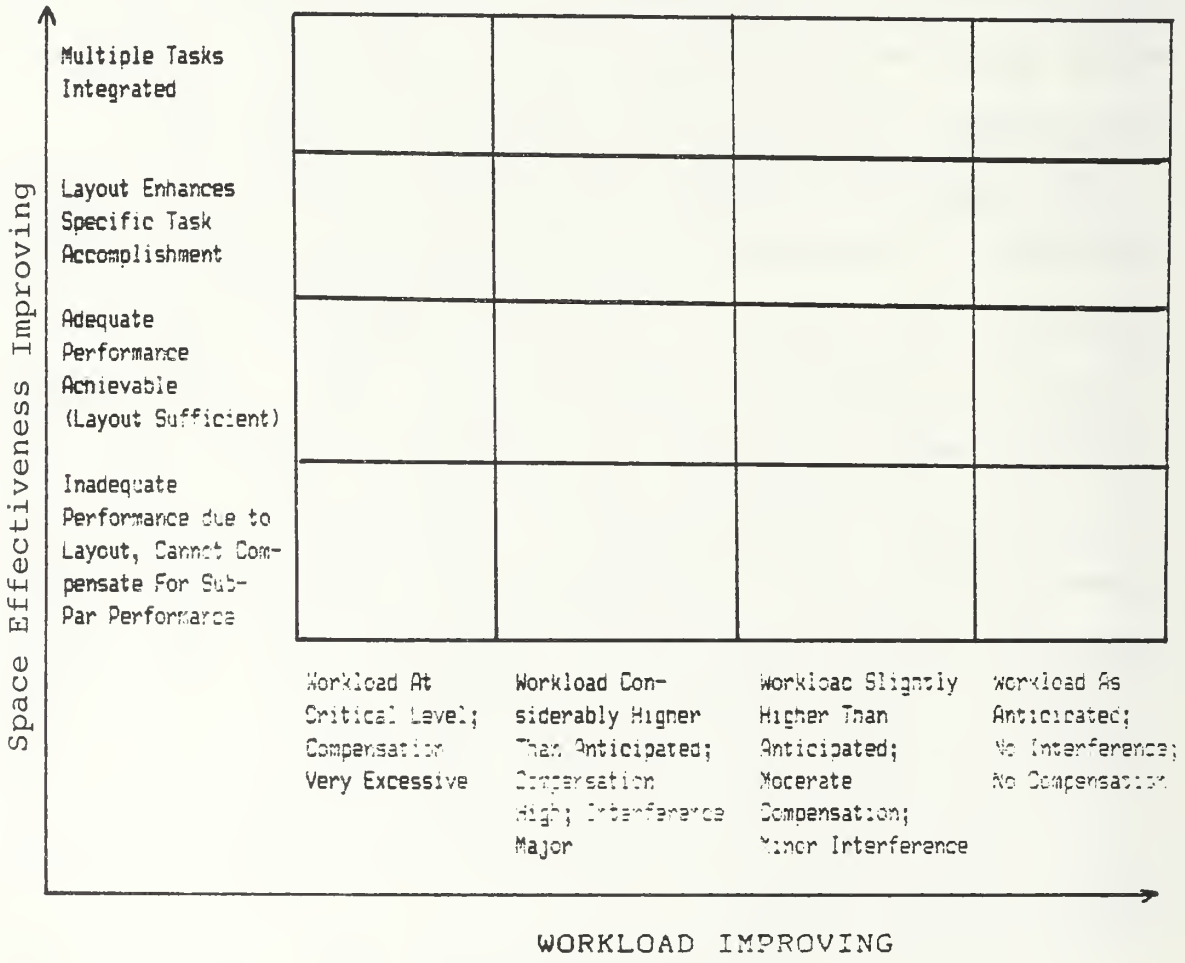
The Link Analysis Questionnaire was designed to determine the frequency of the various links in the EW Module. Combined with the correlation matrix that indicates criticality, this questionnaire determined the weights of the various links. This weighting indicated the most heavily used links. This, in turn, can focus attention on deficiencies in these links. A possible example of this might well be the abnormally long internal communication link between the NTDS console and the WLR-1 position.

The Operator Subtask Questionnaire contained a section requiring an assessment for each of the forty-nine subtasks delineated in Table 1. The subtasks were drawn from a variety of sources (including USS CARL VINSON Combat Direction Center doctrine) and verified by the EW operators prior to the administration of the questionnaire. This assessment was the culmination of the Task Analysis and the beginning of the Operability Analysis. In the Subtask Assessment, each subtask on the questionnaire was evaluated by the EW operators with regards to Operator Workload, Space Effectiveness, and Criticality of the Subtask to the overall mission accomplishment.

The Operator Subtask Questionnaire also contained the Ranking Matrix, where combinations of the various degrees of Operator Workload (OW) and Space Effectiveness (SE) were

TABLE 2. RANKING MATRIX

In the following matrix, the blocks are ranked from best to worst (1 to 16). The lowest numbered block is the intersection of the best of the rows and columns. The number two block is next best, and so on. Note the arrows and the phrases associated with them. Design means the design of the layout or arrangement.



ranked. This was of the utmost importance since the conjoint measurement of the subtask assessment and Module operability depended upon it. Table 2 contains a blank Ranking Matrix. The EW personnel were asked to rank the intersections from best to worst for the "typical" subtask. It was assumed that the rank order for the matrix would vary little from subtask to subtask. Helms found this to be true [Ref. 2:p. 34]. This may have been the most difficult part of the questionnaire and the EW operators were forced to draw upon all their knowledge and previous experience in order to produce a rank order that was meaningful and replicable. This matrix, the intersection of two ordinal scales (OW and SE), is part of conjoint measurement. The Ranking Matrix was expanded and an interval scale constructed via a linear expansion know as the delta method. This resulted in an interval scaling from 0 to 100 and was used to evaluate the total Module operability. The delta method of converting two of these ordinal scales to an interval scale is described in Appendix C.

Using this interval scale, the intersection of any particular set of Operator Workload and Space Effectiveness values on the returned Operator Subtask Questionnaire gives a predetermined Operability Value between 0 and 100. An Operator Workload value between one and four inclusive served to identify a column while a Space Effectiveness value identified a row. The intersection of the row with

the column indicated the assessment of that particular subtask by an operator. For every subtask, this Operability Value was obtained for each rater and the mean and standard deviation were calculated. This mean value represented the Operability Value for that subtask.

The remaining ordinal scale is that of the Criticality. There was no attempt to convert this to an interval scale. Although operators' skills might vary, causing significant deviations in the ratings from rater to rater, there should be only one standard for the criticality of a subtask as it relates to mission accomplishment. This single measure of criticality was taken to be the mean of the criticality ratings. The Operability Value was multiplied by the criticality resulting in a Weighted Operability Value. A Weighted Deficit Value was computed as (100 - Operability Value) multiplied by the Criticality of the subtask. Whereas the Weighted Operability Value will give an indication of the "goodness" of the layout for a particular subtask, the Weighted Deficit Value gives an indication of how much improvement is required to optimize Module Operability for a particular subtask.

The Link Analysis Questionnaire was given approximately one week before the Operator Subtask Questionnaire. It was hoped that the brief exposure to the first questionnaire increased the accuracy of the second.

IV. RESULTS

To test this application, a suitable platform was required. The Electronic Warfare Module on an U.S. Navy aircraft carrier was selected. The particular ship, USS CARL VINSON (CVN-70), was chosen for three reasons: availability, accessibility, and familiarity. CARL VINSON had just returned from a seven month cruise and was in a stand-down period and, so, available. The ship's homeport, Alameda, Ca., was readily accessible for the test. Finally, the ship's layout was familiar enough to the test director to allow a minimum amount of time to be spent on the ship and, therefore, lessen the impact upon the ship's daily work and schedule.

There were limitations to the scope of testing. First, the test was not done at sea which produced two limitations. In regards to Link Analysis, operator usage of the various links and the associated frequencies could not be monitored. This was considered to be a major limitation in regards to only the Link Analysis portion of the test. The compensation for this was the Link Analysis Questionnaire concerning the frequency of link usage. A minor limitation concerned the inability to observe the actual Subtasks and ascertain the criticalities under actual conditions. This

was compensated by the Operator Subtask Questionnaire, which was considered adequate.

A further limitation was the small number of valid responses for the questionnaires. There were three valid responses for the Link Analysis Questionnaire, five for the Rank Ordering portion of the Operator Subtask Questionnaire, and from five to seven for the Subtask Assessment portion of the Operator Subtask Questionnaire. While these numbers are small from a statistical point of view, they can not be discounted. The limited sample size should be an inducement for further testing. Furthermore, the sample size for any aircraft carrier will never be much greater than about twelve due to manning levels. The sample size was seven due to leave and various schools but included the personnel with the most experience. In may be argued that not testing other platforms is a limitation. However, since no two EW Modules on U.S. aircraft carriers are alike, the lack of multiple testing is a moot question.

The test was conducted in the EW Module of USS CARL VINSON (CVN-70). The Module was used so that the personnel could refresh their memory with regards to the layout as they evaluated the subtasks in relation to the layout.

The guidance given to the EW personnel before and during the test stressed that they could ask any question they wished of anyone they wished. They were encouraged to

confer with each other about the workload, effectiveness, and criticality.

A. LINK ANALYSIS

The results of the Link Analysis were taken from the Link Analysis figures and from the Link Analysis Questionnaire. The questionnaire was produced from the Link Analysis figures and the Task Analysis in order to determine the frequency that these links were used. The EW operators on USS CARL VINSON were asked to estimate how many times during a standard eight (8) hour watch they utilized the links. The Link Analysis Questionnaire is listed in Appendix A and the results of the Link Analysis is shown in Table 3.

1. Link Analysis Figures

The most critical links were assessed to be the communication links between operators and the visual links between positions. The criticality of the links were chosen to reflect mission accomplishment and the frequency of usage confirmed the criticality. There were four links considered in the Link Analysis: internal communication, external communication, external visual, and external manual. Of these four, the two most important links are the internal communications and external visual. This is because the external communication will generally involve only one operator (the EW Supervisor/NTDS operator) and there is

TABLE 3. LINK ANALYSIS BY POSITION

Position and Tasks	Frequency	Link	Criticality	Weighted Link Value
WLR-1 Operator:				
1. Talk/communicate with the SLQ-17 operator?	16.667	IC	3	50.00
2. View the presentation on the SLQ-17 console?	77.333	EV	3	231.99
3. Talk/communicate with the NTDS operator?	44.000	IC	3	132.00
4. View the presentation on the NTDS console?	73.333	EV	3	219.99
5. View the NTDS Status Board (SB)?	33.333	EV	1	33.33
6. View the WLR-1 Status Board?	33.333	EV	2	66.67
7. Update the WLR-1 Status Board?	1.667	EM	2	3.34
8. Check (visually) the SLQ-17 computer?	31.000	EV	1	31.00
9. Reboot, reset, or work with the SLQ-17 computer?	1.667	EM	1	1.67
10. Check MUTE?	3.000	EV	2	6.00
11. Change any settings on MUTE?	0.667	EM	2	1.34
SLQ-17 Operator:				
1. Talk/communicate with the NTDS operator?	54.000	IC	3	162.00
2. View the presentation on the NTDS console?	73.333	EV	3	219.99
3. Talk/communicate with the WLR-1 operator?	71.667	IC	3	215.00
4. View the presentation on the WLR-1 console?	48.333	EV	3	144.99
5. View the WLR-1 Status Board?	23.000	EV	3	69.00
6. View the NTDS Status Board?	31.333	EV	3	93.99
7. Update the NTDS Status Board?	9.000	EM	1	9.00
8. Check (visually) the SLQ-17 computer?	26.667	EV	2	53.34
9. Reboot, reset, or work with the SLQ-17 computer?	4.000	EM	3	12.00
10. Check MUTE?	1.000	EV	1	1.00
11. Change any settings on MUTE?	0.667	EM	1	0.67
NTDS Operator/EW Supervisor:				
1. Talk/communicate with the SLQ-17 operator?	45.667	IC	3	136.99
2. View the presentation on the SLQ-17 console?	65.667	EV	3	197.00
3. Talk/communicate with the WLR-1 operator?	72.333	IC	3	216.99
4. View the presentation on the WLR-1 console?	60.667	EV	3	182.00
5. View the WLR-1 Status Board?	45.000	EV	3	135.00
6. View the NTDS Status Board?	48.333	EV	3	144.99
7. Update the NTDS Status Board?	16.000	EM	3	48.00
8. Check (visually) the SLQ-17 computer?	34.667	EV	1	34.67
9. Reboot, reset, or work with the SLQ-17 computer?	4.000	EM	1	4.00
10. Check MUTE?	6.667	EV	1	6.67
11. Change any settings on MUTE?	4.000	EM	1	4.00
12. Communicate outside the Module?	35.333	EC	3	105.99

KEY: IC - Internal Communications; EC - External Communications;
EV - External Visual; EM - External Manual

little requirement for manual links outside of ones own position. An external communications link example is the link between the EW Supervisor/NTDS operator and the communications that enable him to communicate outside the Module. However, this requires that the operator rise from his seat to communicate. As a remedy, the NTDS operator uses a hand mike that hangs down near his console. This is a partial solution because he still needs to rise from his seat to select another station on the communication box. Additionally, the hand mike hanging so close to his console presents a clutter problem.

Note that the communication and visual link between the NTDS operator (EW Supervisor) and the WLR-1 operator is the longest and partially blocked. The links between the WLR-1 operator and the NTDS operator and SLQ-17 operator are long, allowing him to view very little of the environment. The WLR-1 operator's visual links are very long and the parallax effect severely degrades his observation. Note the long link lines between the SLQ-17 and NTDS positions and the WLR-1 Status Board, and the WLR-1 operator and the NTDS Status Board. Finally, note the very long external visual links to the SSQ-82 MUTE and that they cross. MUTE is required to be checked periodically for faults or changes in the various monitor boxes. The distance is great enough between MUTE and the rest of the Module that only the WLR-1

operator can effectively monitor it. However, this requires considerable movement on the part of the WLR-1 operator.

2. Link Analysis Table

The frequency of the various links were determined by the Link Analysis Questionnaire. The ideal way to determine link frequency is to count the actions/link interactions during the watch. Since this was not possible, the questionnaire approach was chosen. The Link Analysis is intended here to focus attention at the links that are used most often. The frequency of link usage is multiplied by the weight (criticality) of the link and an indication of its relative importance is determined.

When the links associated with the WLR-1 operator are considered, it can be noted the longest links are the internal communication and external visual links between him and the SLQ-17 and NTDS positions. These links are also the most critical and the most frequently used. The average number of times the operator tries to view the NTDS console is 73.333. Yet this console is the furthest away (see Figures 4 and 5). The WLR-1 operator communicates more with the NTDS operator for two reasons. Many times the NTDS operator is also the EW Supervisor. The fullest picture of the entire environment of surface, subsurface, and air contacts is present on the NTDS. The other large frequency usage is the visual links for the presentation on the SLQ-17

console. This console is only slightly closer than the NTDS console.

In the case of the SLQ-17 operator, the first six entries in Table 3 are the ones with the greatest criticality and the highest frequency of use. The high criticality and frequency associated with checking the SLQ-17 computer is understandable since the SLQ-17 operator is specifically trained to know what to look for on the computer face. Note that the SLQ-17 operator views the presentation at the NTDS console much more than that at the WLR-1 position. It can be seen from Figure 5 that these external visual links between the SLQ-17 and the NTDS are much shorter than between SLQ-17 and the WLR-1. At the same time, the SLQ-17 operator communicates more with the WLR-1 operator than with the NTDS operator. This suggests that the SLQ-17 operator gets a better picture of the environment from the NTDS but better information concerning the environment from the WLR-1.

The NTDS operator/EW Supervisor are combined because many times the EW Supervisor will man the NTDS console for a major portion of the watch. This is necessary because all the external communications are at or near the NTDS console. Note the large frequency and high criticality associated with communications outside the Module (external communications link). There appears to be a reversal of interaction between the NTDS operator/EW Supervisor and the

WLR-1 and SLQ-17 positions. He views the SLQ-17 console more than communicates with the operator but talks more to the WLR-1 operator than views the WLR-1 displays. Recall from Figures 4 and 5 that both the internal communications and the external visual links between NTDS and WLR-1 are very long. Additionally, note how much he looks at the WLR-1 Status Board even though it is the furthest away (Figure 6).

The Link Analysis is important since it serves to indicate which links are long, important, and possibly overworked. As such it can be used as a starting point in the redesign of a layout by showing which links need to be reduced in length. The Link Analysis results should also support the results of the Operability Analysis.

B. OPERABILITY ANALYSIS

The Operator Subtask Questionnaire was divided into two parts: the Subtask Assessment and the Ranking Matrix. The Subtask Assessment was given first. The criteria for this evaluation and the test itself are given in Appendix A.

The second half of the Operator Subtask Questionnaire was the Ranking Matrix. All returned valid rankings (n=5) were entered into the matrix and a mean determined for each block and the matrix numbered accordingly. The standard deviation was calculated in case of a tie. This matrix with the mean rank values and the standard deviation is

illustrated in Table 4. The resultant rank matrix is shown in Table 5.

Next this rank ordering was converted to an interval scale. This was done by reversing the order of the numbering so that the best of the Operator Workload and Space Effectiveness is #16 and the worst is #1 (see Table 6). Using this as a base, the delta method of linear expansion was used to determine an interval scale. See Appendix C for a brief description, example of the delta method, and the final work sheet for this application.

Table 7 shows the result of the delta method which is the desired interval scale. The results of the delta method were normalized by dividing all the blocks by the highest value in the block; in this application it was 102. Table 8 is the normalized interval scale for this application.

The Operability Value was weighted (multiplied) by the mean assessed Criticality of that particular Subtask to derive the Weighted Operability Value. The Weighted Operability Value has the potential to range from an absolute minimum of 0 (0x1) to an absolute maximum of 500 (100x5). The range noted was 14.14 to 418.87.

The Weighted Deficit Value gives an indication of how much improvement is needed to optimize Layout Effectiveness for a particular Subtask. The greatest Weighted Deficit Value was 485.00 while the least was 28.09. The Weighted

TABLE 4. MEAN RANK ORDER AND STANDARD DEVIATION FOR EACH RATING MATRIX CELL

9.6 2.50	4.6 1.14	2.4 0.55	1
11.0 2.55	8.0 1.58	5.2 1.10	2.8 0.84
13.8 1.64	10.8 1.10	8.8 1.10	5.4 1.34
16	14.0 1.22	12.2 2.17	10.4 3.13

Mean Rank Standard Deviation

TABLE 5. RANK ORDER OF OPERATOR RATING MATRIX

SE \ OW	1	2	3	4
4	9	4	2	1
3	12	7	5	3
2	14	11	8	6
1	16	15	13	10

TABLE 6. FINAL RANK ORDER INVERTED FOR DELTA METHOD

SE				
4	8	13	15	16
3	5	10	12	14
2	3	6	9	11
1	1	2	4	7
	1	2	3	4

OW

TABLE 7. DELTA METHOD SOLUTION FOR OPERATOR SUBTASK RATING SCALE

	0	22	35	47	
4	55	77	90	102	55
3	40	62	75	87	40
2	24	46	59	71	24
1	0	22	35	47	0
	1	2	3	4	

SE

OW

TABLE 8. NORMALIZED INTERVAL SCALE

SE	0	21	34	46	
4	54	75	89	100	54
3	40	61	74	86	40
2	24	45	58	70	24
1	0	21	34	46	0
	1	2	3	4	

OW

Deficit Value can range from 500 to 0. The larger the number, the greater the amount of improvement is needed.

The Total Module Operability for this particular EW Module was computed to be 39.2 %. This computation is as follows. There were 49 Subtask evaluated. The summation of the criticalities of these Subtasks in order to accomplish the mission was 200.84. By assuming a perfect layout, we can multiply by 100 to obtain a maximum score of 20,084. Next the Weighted Operability Values were summed to obtain the actual score of the Module of 7872.31. When the actual score is divided by the maximum, an indication of the effectiveness of the layout is obtained.

Table 9 contains an ordering of the Subtasks by cumulative weight. This was determined by dividing the Weighted Deficit Value by the optimum layout effectiveness to determine how much the deficit each Subtasks comprises. These were then ranked from most to least. This table gives an indication of which Subtasks should be improved first in order to achieve the most cost effective approach to improving the Module.

Table 9 contains the rank ordering by cumulative weights, the Subtask number, a brief description of the Subtask and its associated position, the operators polled with their evaluation of the Subtask in terms of Operator Workload and Space Effectiveness converted to an interval scale, the operability value (the mean of the operators'

TABLE 9. RANK ORDER OF SUBTASKS BY CUMULATIVE WEIGHT

No.	Subtask	Description (Pos)	01	02	03	04	05	06	07	Operability Value	Deficit Value	Criticality	Weight	Cumulative Total%
1	1.2.1	Rprt EW Info (Sup)	21	0	0	0	0	0	0	3.000	97.000	5.000	3.97	3.97
2	1.2.2	Prov EW Recom (Sup)	21	0	0	0	0	0	0	3.000	97.000	5.000	3.97	7.94
3	4.1.1	Srch Assgn Bnds (WLR)	0	0	0	0	21	0	0	3.000	97.000	5.000	3.97	11.91
4	4.2.2	Rprt EW Info (WLR)	34	0	0	0	0	21	0	7.857	92.143	5.000	3.77	15.68
5	4.2.1	Prv ESM - NTDS (WLR)	21	0	0	0	0	0	0	3.000	97.000	4.714	3.74	19.42
6	4.1.4	DF Signals (WLR)	21	0	0	0	58	0	0	11.286	88.714	5.000	3.63	23.05
7	4.1.2	Analyze Sigs (WLR)	0	0	0	0	21	0	0	14.286	85.714	5.000	3.51	26.56
8	5.1.1	Communicate (SB)	21	24	0	21	0	0	21	10.573.	89.427	4.571	3.35	29.91
9	2.1.1	Enter ID's (NTDS)	45	21	0	0	0	0	0	9.857	90.143	4.500	3.32	33.23
10	4.2.4	Log Intercepts (WLR)	0	0	0	0	70	24	0	13.429	86.571	4.571	3.24	36.47
11	2.1.4	Enter EW Fix (NTDS)	34	0	0	21	100	0	0	22.143	77.857	5.000	3.19	39.66
12	2.1.2	Enter ESM Info (NTDS)	45	0	0	21	0	0	0	9.857	90.143	4.714	3.08	42.74
13	5.1.3	Update SB (SB)	45	0	0	34	21	21	21	20.289	79.711	4.714	3.08	45.82
14	2.1.5	Brng Resolution (NTDS)	58	21	0	45	21	0	21	23.714	76.286	4.429	2.77	48.59
15	2.1.3	Trngle ESM Brng (NTDS)	21	0	0	21	88	0	45	25.000	75.000	4.429	2.72	51.31
16	1.1.6	Man ID Request (SUP)	21	34	0	34	—	21	—	22.000	78.000	4.000	2.56	53.87
17	1.1.4	Assign ESM Srch (Sup)	58	34	0	21	58	0	0	24.429	75.571	4.000	2.48	56.35
18	5.1.2	Advise Module (SB)	34	21	21	21	0	0	74	24.429	75.571	4.000	2.48	58.83
19	2.2.1	Report EW Info (NTDS)	45	61	0	58	58	21	0	34.714	65.286	4.571	2.44	61.27
20	1.2.5	Nav by ESM (Sup)	21	21	34	21	0	21	74	17.500	82.500	3.500	2.37	63.64
21	3.2.4	Update SB (17)	21	45	21	21	21	21	21	24.857	75.143	3.571	2.28	65.84
22	1.1.3	Assign ESM resp (Sup)	—	45	34	45	21	—	75	44.000	56.000	4.500	2.06	67.90
23	1.1.5	Man ID Rqust-ship (Sup)	58	34	21	45	—	46	—	40.800	59.200	4.250	2.06	69.96
24	3.1.5	Evaluate Data (17)	45	45	45	21	100	21	45	46.000	54.000	4.571	2.02	71.98
25	3.1.3	Enter Parameters (17)	40	54	54	54	21	54	40	45.286	54.714	4.429	1.98	73.96
26	4.3.4	Monitor MUTE (WLR)	34	34	34	34	21	34	58	35.571	64.429	3.714	1.96	75.92
27	1.2.4	De/Brief Airwing (Sup)	34	21	34	21	0	21	74	29.286	70.714	3.286	1.98	77.82
28	4.3.1	Monitor EMCON (WLR)	58	21	61	58	21	61	45	46.429	53.571	4.286	1.88	79.70
29	4.3.2	Rprt EMCON (WLR)	58	34	46	58	21	46	46	44.143	55.857	3.857	1.76	81.46
30	1.3.1	EDM Criteria (Sup)	58	58	88	45	21	45	—	52.500	47.500	4.500	1.75	83.21
31	1.1.2	Assign Search (Sup)	58	45	34	45	21	70	75	49.714	50.286	4.143	1.71	84.92
32	3.1.1	Monitor AutoCrrltn (17)	61	75	54	75	0	75	24	52.000	48.000	4.286	1.69	86.61
33	2.1.6	Eval ESM Brng (NTDS)	70	74	74	58	21	45	58	57.143	42.857	4.286	1.58	88.11
34	2.2.2	Update SB (NTDS)	45	74	74	58	21	45	45	51.714	48.286	3.571	1.41	89.52
35	4.3.3	Log Violations (WLR)	58	58	34	46	70	34	45	49.286	50.714	3.000	1.25	90.77
36	1.2.3	Update SB (Sup)	70	58	58	58	58	58	61	60.143	39.857	3.714	1.21	91.98
37	3.2.1	Report EW (17)	86	100	86	86	21	86	0	66.429	33.571	4.286	1.18	93.16
38	3.2.2	Provide Data (17)	86	86	74	74	58	70	24	67.429	32.571	4.000	1.07	94.23
39	3.3.2	Estab EDM Modes (17)	70	100	100	86	45	100	0	71.714	28.286	4.571	1.06	95.29
40	4.1.5	Assist Eval EDM (WLR)	34	34	34	100	34	46	58	48.571	51.429	2.286	0.96	96.25
41	3.1.2	Estab Op Modes (17)	86	100	100	100	58	75	45	80.571	19.714	3.857	0.61	97.86
42	1.1.1	Assign SLQ-17 (Sup)	70	100	100	100	58	58	75	80.143	19.857	3.167	0.52	97.38
43	3.3.3	Assist EDM Employ (17)	58	100	100	100	58	100	88	82.286	17.714	3.333	0.48	97.86
44	3.2.3	Monitor EW Entry (17)	70	100	86	74	46	100	74	78.571	21.429	2.571	0.45	98.31
45	3.3.1	Engage Trgts-EDM (17)	74	100	86	74	100	100	88	88.857	11.143	4.714	0.43	98.74
46	3.1.4	Monitor Envrnmnt (17)	86	100	100	100	86	100	45	88.143	11.857	4.000	0.39	99.13
47	4.2.3	Update SB (WLR)	58	100	100	86	58	100	74	82.286	17.714	2.429	0.35	99.48
48	1.1.7	Monitor SLQ-17 (Sup)	86	100	100	100	70	86	—	90.333	9.667	3.667	0.29	99.77
49	4.1.3	Check Images (WLR)	70	100	100	100	58	100	86	87.714	12.286	2.286	0.23	100.00

evaluations), the deficit value (100 - operability value), the mean criticality, the cumulative weight or percentage of the total deficit that that particular Subtask comprises, and the total percentage.

V. DISCUSSION AND RECOMMENDATIONS

There has been no attempt to ascertain what Weighted Deficit Value or Weighted Operability Value is acceptable. This is beyond the scope of this effort. The purpose has been to identify which areas are in need of improvement and what areas should be addressed first in order to realize the greatest amount of improvement for a given effort. To answer the question of what Weighted Deficit or Operability Value is acceptable will call for additional research targeting the Subtasks individually to a greater detail than was attempted here.

A. LINK ANALYSIS DISCUSSION

The Link Analysis results show that there is only one position that might be considered acceptable in relation to the lengths of its links. This is the SLQ-17 position. This can be seen in part from the relatively good showing that the SLQ-17 console position had in comparison to the other two positions. The SLQ-17 operator can easily view what is displayed on the NTDS console and, without excessive movement, view the WLR-1 displays. He is within good viewing distance of the NTDS Status Board and his own SLQ-17 computer. The viewing distance to the WLR-1 position and its associated Status Board are rather long, but still viewable. Because of its relatively good positioning in

relation to the rest of the Module, SLQ-17 entries were much lower in Table 9. This would indicate that the layout actually promotes increased operator compensation since the other positions did not score as well. A score of 39.2% is an indication of a poor the Module layout contributing to an increased operator compensation burden. Were the module layout better, the operators would have felt much better about the Module and the score would have been higher.

B. OPERABILITY ANALYSIS DISCUSSION

Several observations can be made from Table 9. First, the SLQ-17 appears to be the best position in the EW Module since its first entry is in twenty-first place in the table and most of the entries are at the bottom of the table. Almost 27% of the possible improvements can be made in the first seven entries and these are just for the EW Supervisor and the WLR-1 operator. Note that the criticalities of these Subtasks are the highest. In other words, these Subtasks which are very critical are poorly supported by the layout, relative to the less critical Subtasks. Most of the lower criticalities are associated with Subtasks that have a relatively good layout effectiveness.

It can be reasonably argued that Module Operability of 39.2% is not sufficient for an EW Module. What can not be argued is how much improvement is enough. Nor can it be extrapolated from this study what improvement a

rearrangement can result in. However, it can be seen that improvement can be made in certain areas, as is indicated by careful perusal of Table 9.

C. EXTRAPOLATION

Further, this approach can be used for possible extrapolations. For example, comparing Figure 1 and Figure 2, similarities are noted. They have the same arrangement of positions (i.e., from left to right, WLR-1, SLQ-17, and NTDS). The positions are arranged in "straight line" type of layout. This resulted in a low Layout Effectiveness rating for USS CARL VINSON. It may be readily conjectured that another arrangement would work better, namely, a "crescent" shaped layout with the NTDS in between WLR-1 and SLQ-1 and the supervisor's position raised and directly in back of the NTDS operator.

D. CONCLUSION

It can be concluded that the present configuration of the EW Module on USS CARL VINSON does not result in an optimal utilization of this Module in terms of EW mission accomplishment. Further, there is a real need to assess the layout operability of the warfare modules onboard U.S. Naval combatants. This thesis has provided one way in which a measure of the effectiveness of a particular layout can be

determined. Although this was a limited test, indications are that this approach works, and further testing is warranted.

Building a new layout is urged with the hopes that it may prove by testing to be better than the last one, using the Link Analysis and Operability Analysis illustrated in this work. What is significant and useful from the Link Analysis is that any improvement in layout design should probably start with ensuring that the critical links are not overly long or taxed beyond their limit. Any improvement to the layout design should take into account these critical links to reduce them to their optimum and any changes must not adversely affect the links since in that case any gain in layout design may be cancelled by a loss in link utilization. By conducting tests at landbased test sites, the risks of error are reduced. By the utilization of mock-ups and fleet inputs, the risks can be reduced even further. The result is a more effective layout enhancing mission accomplishment.

E. RECOMMENDATION

It is recommended that a land based test facility be established that would incorporate the ideas, recommendations, and methods indicated in this thesis as a first step to upgrading our combat workspaces.

APPENDIX A

OPERATOR SUBTASK QUESTIONNAIRE

GENERAL INSTRUCTIONS

The purpose of this questionnaire is a subjective evaluation of the layout effectiveness of the EW Module for use in an algorithm to determine, in an objective sense, the effectiveness of the layout in accomplishing the mission of the Module. To do this there is a series of subtasks differentiated by operator that must be assessed in terms of operator workload per subtask, space effectiveness per subtask, and criticality of the subtask toward overall mission accomplishment. What is required is to make this assessment based on your experience and expertise. There is no time limit, you may ask questions of anyone you wish, and you should go and look at the Module to make sure of your answers especially if you are unsure of some of the questions concerning movements. There are no right or wrong answers, but try to be as precise as you can. A scenario, hopefully similar to your recent operations in the Sea of Japan, has been constructed. For each of the subtasks on the next page, mark with an "X", the description that best describes the operator workload (OW) and the space effectiveness (SE). If the arrangement of the space has little or no effect on subtask accomplishment, then it would

rate the highest (4). Conversely, if the layout or arrangement of the space negatively impacts subtask accomplishment, then it would rate a (1). Give your assessment of the criticality of the subtask in relation to the overall mission accomplishment. The descriptions of criticality, operator workload, and space effectiveness are listed on a separate sheet.

SCENARIO

This scenario begins with the assumption of the watch by a particular section

They are the on-coming watch section in the EW module of a NIMITZ class aircraft carrier that is steaming in the open ocean with six escorts. The escorts are one VIRGINIA class cruiser, two SPRUANCE class destroyers, one OLIVER HAZARD PERRY class frigate, one LOS ANGELES class submarine, and an oiler. There are heightened tensions world-wide with a probable confrontation between the two super-powers. There is a Soviet task group within 200 NM. The task group is comprised of a KIEV class aircraft carrier, a KIROV class cruiser, a SOVERMENYY class destroyer, two KRIVAK III class frigates, a SLAVA class destroyer, and three auxiliaries. Additionally, ECHO II, VICTOR III, and OSCAR class submarines are known to be in the area but unlocated for the past twelve hours. A Mod-KASHIN is the tattletale for the

Battle Group. Both forces are within range of Soviet air power.

General Quarters is not set, but a heightened Condition III steaming watch is manned. There has been a momentary lapse of 400 Hz power and the NTDS is being reloaded. The SLQ-17 needs to be reloaded and reprogrammed. As the NTDS is brought on the line, the WLR-1 operator is told to recheck the past entries in his log and verify that they are still active. After 15 minutes, the WLR-1 operator reports that he has intercepted several new signals. One is an airborne mapping and reconnaissance radar. One appeared to be a brief intercept of a submarine radar. Another is an air search radar and the last is a missile acquistion radar.

The NTDS air trackers report jamming on both long range and 3-D air search radars.

The SLQ-17 alarms and displays hostile missile symbols from both the suspected direction of the SOviet task group and two angles 30 degrees either side of the task group.

Deck Launched Interceptors are airborne within one minute.

The EW operator at the NTDS console is entering ESM bearing lines and attempting to identify unknown contacts. The SLQ-17 operator shifts operation of the ECM portion to automatic as the TAO frees weapons. The WLR-1 operator is attempting to search the known hostile missile homing radar ranges to facilitate identification. General Quarters is

sounded. The TAO orders EMCON to be set for battle and the WLR-1 operator selects EMCON D on MUTE. A quick check of both the NTDS scope and that of the SLQ-17 indicates that the number and direction of the inbound unknowns do not match. The EW watch section tries to match the emerging identification from the WLR-1 and SLQ-17 to both the SLQ-17 and the NTDS presentations.

If you have trouble envisioning this scenario, recall the Sea of Japan operations on your last deployment and consider the signal environment and tactics you saw then.

OPERATOR WORKLOAD, SPACE EFFECTIVENESS, and CRITICALITY

WORKLOAD/COMPENSATION/INTERFERENCE (Mental and Physical)

(1)	(2)	(3)	(4)
Workload Extreme Compensation Extreme Interference Extreme	Workload High Compensation High Interference High	Workload Moderate Compensation Moderate Interference Moderate	Workload Low Compensation Low Interference Low

SPACE EFFECTIVENESS

(1)	(2)	(3)	(4)
Inadequate Performance Due to Layout	Adequate Performance Achievable; Layout Sufficient to Specific Task	Layout Enhances Specific Task Accomplishment	Layout Design Integrates Multiple Tasks

CRITICALITY: How important is it that the operator/team be able to perform this task as compared to the other tasks in successfully completing the mission?

Scale Value:

(1) Of very small importance. Ability to perform this task as compared to other tasks in this duty is unimportant, or almost unimportant, in order to successfully complete the mission of the Module.

(2) Of small importance. This task within this duty is less important than most tasks required to successfully complete the mission of the Module.

(3) Of moderate importance. This task within this duty is about as important as most tasks required to successfully complete the mission of the Module.

(4) Of substantial importance. This task within this duty is more important than most tasks required to successfully complete the mission of the Module.

(5) Of extreme importance. This task within this duty is extremely important in order to successfully complete the mission of the Module.

EW Supervisor

Task: 1.1 Direct ESM search
Subtasks
1.1.1 Assign search parameters to SLQ-17

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

1.1.2 Assign search parameters to WLR-1

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

1.1.3 Assign ESM sensor report responsibilities -- own ship

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

1.1.4 Assign ESM sensor report responsibilities -- force

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

1.1.5 Initiate manual ID request - ship

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

1.1.6 Initiate manual ID request - force

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

1.1.7 Monitor automatic correlations/associations, (SLQ-17)

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

Task: 1.2 Report/Disseminate EW Information
Subtasks
1.2.1 Report evaluated EW information

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

1.2.2 Provide EW recommendations

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

1.2.3 Update status board near NTDS console

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

1.2.4 Brief/debrief embarked Airwings

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

1.2.5 Navigation by passive EW

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

Task: 1.3 Counter Hostile Environment
Subtasks

1.3.1 Promulgate ECM employment criteria

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

NTDS Operator

Task: 2.1 Collect and enter EW data into NTDS
Subtasks
2.1.1 Enter manual ID information into NTDS

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

2.1.2 Enter manual ESM/NTDS track associations

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

2.1.3 Perform triangulation of ESM bearing lines

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

2.1.4 Enter EW fixes

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

2.1.5 Advise operators of bearing resolution

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

2.1.6 Evaluate externally reported ESM bearings

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

Task: 2.2 Report/Disseminate EW Information
Subtask
2.2.1 Report evaluated EW information

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

2.2.2 Update status board near console

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

SLQ-17 Operator

Task: 3.1 Conduct ESM Search
Subtask
3.1.1 Monitor automatic correlations/associations

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

3.1.2 Establish operating modes of SLQ-17 (ESM)

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

3.1.3 Enter detection and response parameters (ESM/ECM)

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

3.1.4 Monitor environment on NTDS console

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

3.1.5 Evaluate displayed data

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

Task: 3.2 Report/Disseminate EW Information
Subtask
3.2.1 Report evaluated EW information

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

3.2.2 Provide ESM/ECM data to NTDS

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

3.2.3 Monitor entry of EW data into NTDS

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

3.2.4 Update status board

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

Task: 3.3 Counter Hostile Environment
Subtask
3.3.1 Engage targets with ECM

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

3.3.2 Establish ECM operating Modes

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

3.3.3 Assist in promulgation of ECM employment criteria

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

WLR-1 Operator

Task: 4.1 Conduct ESM Search
Subtasks

4.1.1 Search assigned bands

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

4.1.2 Analyze intercepted signals

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

4.1.3 Check intercepts for images/harmonics

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

4.1.4 Accurately DF intercepted signals

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

4.1.5 Assist in evaluating ECM

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

Task: 4.2 Report/Disseminate EW Information
Subtasks
4.2.1 Provide ESM data to NTDS

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

4.2.2 Report evaluated EW information

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

4.2.3 Update status board near position

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

4.2.4 Log all intercepts

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

Task: 4.3 EMCON
Subtasks
4.3.1 Monitor EMCON

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

4.3.2 Report violations of EMCON

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

4.3.3 Log violations of EMCON

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

4.3.4 Monitor MUTE

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

EW Status Board

Task: 5.1 Maintain Status Boards
Subtasks
5.1.1 Communicate with operators

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

5.1.2 Advise operators of any information received

Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

5.1.3 Update status boards

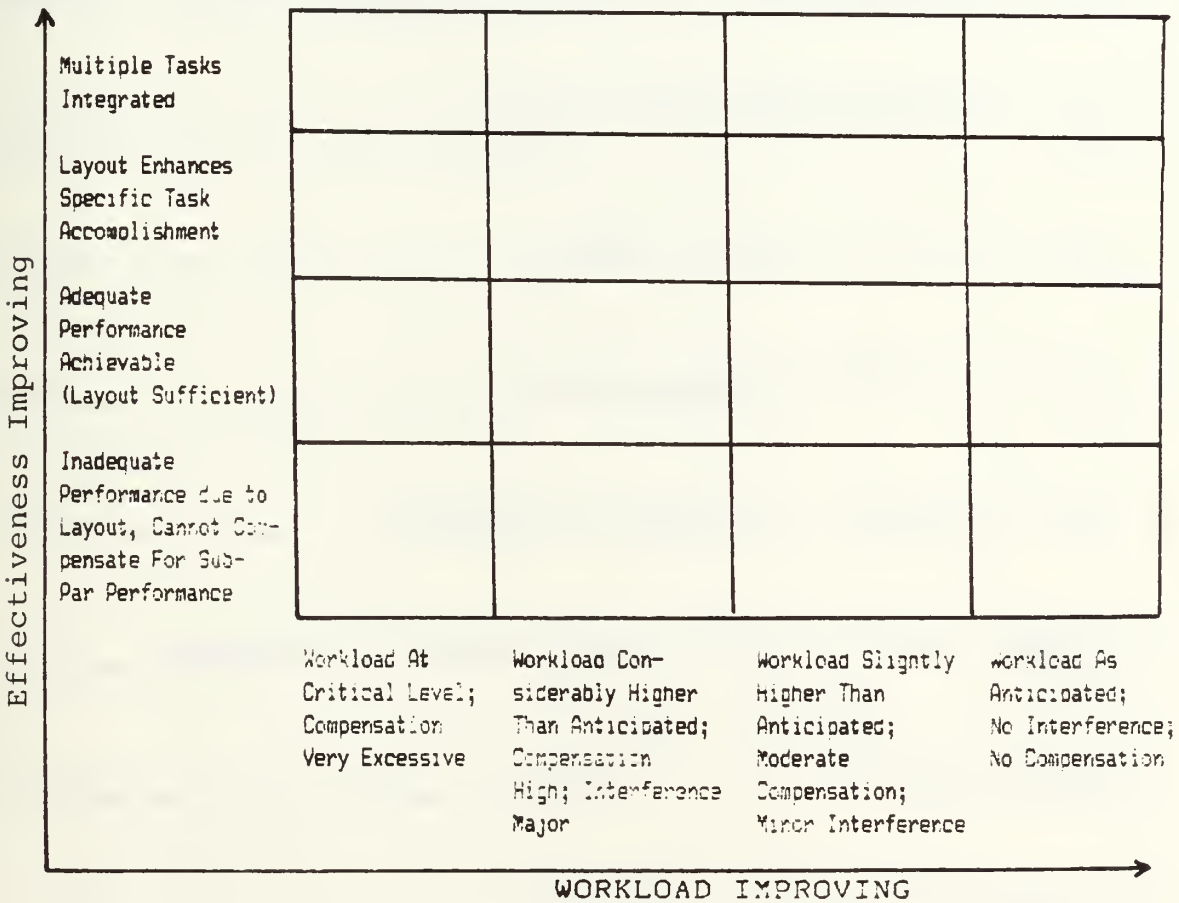
Operator Workload: _____ _____ _____ _____
(1) (2) (3) (4)

Space Effectiveness: _____ _____ _____ _____
(1) (2) (3) (4)

Criticality: _____

Rating Matrix Cell Rank Order

For the following matrix, rank the blocks from best to worst (1 to 16). The lowest numbered block is the intersection of the best of the rows and columns. The number two block is next best, and so on. Note the arrows and the phrases associated with them. Design means the design of the layout or arrangement. Do not think of the layout of one workstation, such as the WLR-1 or SLQ-17, but of the entire EW Module. Think of the scenario already presented in order to properly consider the workload. Ask any questions you want or talk among yourselves or go and look at the layout.



LINK ANALYSIS QUESTIONNAIRE

WLR-1 Operator:

How many times in an eight hour watch do you:

1. Talk/communicate with the SLQ-17 operator? ____

2. View the presentation on the SLQ-17 console? ____

3. Talk/communicate with the NTDS operator? ____

4. View the presentation on the NTDS console? ____

5. View the NTDS Status Board (SB)? ____

6. View the WLR-1 Status Board? ____

7. Update the WLR-1 Status Board? ____

8. Check (visually) the SLQ-17 computer? ____

9. Reboot, reset, or work with the SLQ-17 computer? ____

10. Check MUTE? ____

11. Change any settings on MUTE? ____

SLQ-17 Operator:

How many times in an eight hour watch do you:

1. Talk/communicate with the NTDS operator? ____

2. View the presentation on the NTDS console? ____

3. Talk/communicate with the WLR-1 operator? ____

4. View the presentation on the WLR-1 console? ____

5. View the WLR-1 Status Board? ____

6. View the NTDS Status Board? ____

7. Update the NTDS Status Board? ____

8. Check (visually) the SLQ-17 computer? ____

9. Reboot, reset, or work with the SLQ-17 computer? ____

10. Check MUTE? ____

11. Change any settings on MUTE? ____

NTDS Operator/EW Supervisor:

How many times in an eight hour watch do you:

1. Talk/communicate with the SLQ-17 operator? ____

2. View the presentation on the SLQ-17 console? ____

3. Talk/communicate with the WLR-1 operator? ____

4. View the presentation on the WLR-1 console? ____

5. View the WLR-1 Status Board? ____

6. View the NTDS Status Board? ____

7. Update the NTDS Status Board? ____

8. Check (visually) the SLQ-17 computer? ____

9. Reboot, reset, or work with the SLQ-17 computer? ____

10. Check MUTE? ____

11. Change any settings on MUTE? ____

12. Communicate outside the Module? ____

APPENDIX B

QUESTIONNAIRE RESULTS

Rating Matrix Cell Rank Order

In the following matrix, the blocks rank from best to worst (1 to 16). The lowest numbered block is the intersection of the best of the rows and columns. The number two block is next best, and so on. Note the arrows and the phrases associated with them. Design means the design of the layout or arrangement.

Multiple Tasks Integrated	9	6	2	1
Layout Enhances Specific Task Accomplishment	12	7	4	3
Adequate Performance Achievable (Layout Sufficient)	14	11	10	5
Inadequate Performance due to Layout, Cannot Compensate For Sub-Par Performance	16	15	13	8
	Workload At Critical Level; Compensation Very Excessive	Workload Considerably Higher Than Anticipated; Compensation High; Interference Major	Workload Slightly Higher Than Anticipated; Moderate Compensation; Minor Interference	Workload As Anticipated; No Interference; No Compensation

RESULTANT INTERVAL SCALE for OPERABILITY

Multiple Tasks Integrated	54	75	88	100
Layout Enhances Specific Task Accomplishment	40	61	74	85
Adequate Performance Achievable (Layout Sufficient)	24	45	58	70
Inadequate Performance due to Layout, Cannot Compensate For Sub-Par Performance	0	21	34	46
	Workload At Critical Level; Compensation Very Excessive	Workload Considerably Higher Than Anticipated; Compensation High; Interference Major	Workload Slightly Higher Than Anticipated; Moderate Compensation; Minor Interference	Workload As Anticipated; No Interference; No Compensation

RESULTS OF ALL OPERATORS

NOTES: The following results are the Operability Value of all responses for each subtask. Generally, n equalled 7 for the subtasks, although there were some with only six responses. The Standard Deviation is that of the sample and not the population (i.e., the standard deviation was calculated using n vice n-1). The Interval Scale shown was based on the Ranking Scale which the EW operators provided through the questionnaire. The Ranking (an ordinal) Scale was then converted to an interval scale by means of the Delta Method (a linear expansion). The Criticality listed is a mean for the subtask. The Weighted Operability Value is simply the Operability Value weighted (multiplied) by the Criticality.

EW Supervisor

Task: 1.1 Direct ESM search
Subtasks
1.1.1 Assign search parameters to SLQ-17

Operability Value:	80.143
Criticality:	3.167
Weighted Operability Value:	253.81
Weighted Deficit Value:	62.89

1.1.2 Assign search parameters to WLR-1

Operability Value:	49.714
Criticality:	4.143
Weighted Operability Value:	205.97
Weighted Deficit Value:	208.33

1.1.3 Assign ESM sensor report responsibilities -- own ship

Operability Value:	44.000
Criticality:	4.500
Weighted Operability Value:	198.00
Weighted Deficit Value:	252.00

1.1.4 Assign ESM sensor report responsibilities -- force

Operability Value:	24.429
Criticality:	4.000
Weighted Operability Value:	97.72
Weighted Deficit Value:	302.28

1.1.5 Initiate manual ID request - ship

Operability Value:	40.800
Criticality:	4.250
Weighted Operability Value:	173.40
Weighted Deficit Value:	251.60

1.1.6 Initiate manual ID request - force

Operability Value:	22.000
Criticality:	4.000
Weighted Operability Value:	88.00
Weighted Deficit Value:	312.00

1.1.7 Monitor automatic correlations/associations, (SLQ-17)

Operability Value:	90.333
Criticality:	3.667
Weighted Operability Value:	331.25
Weighted Deficit Value:	35.45

Task: 1.2 Report/Disseminate EW Information
Subtasks
1.2.1 Report evaluated EW information

Operability Value:	3.000
Criticality:	5.000
Weighted Operability Value:	15.00
Weighted Deficit Value:	485.00

1.2.2 Provide EW recommendations

Operability Value:	3.000
Criticality:	5.000
Weighted Operability Value:	15.000
Weighted Deficit Value:	485.00

1.2.3 Update status board near NTDS console

Operability Value:	60.143
Criticality:	3.714
Weighted Operability Value:	223.37
Weighted Deficit Value:	148.03

1.2.4 Brief/debrief embarked Airwings

Operability Value:	29.286
Criticality:	3.286
Weighted Operability Value:	96.23
Weighted Deficit Value:	232.37

1.2.5 Navigation by passive EW

Operability Value:	17.500
Criticality:	3.500
Weighted Operability Value:	61.25
Weighted Deficit Value:	288.75

Task: 1.3 Counter Hostile Environment
Subtasks
1.3.1 Promulgation of ECM employment criteria

Operability Value:	52.500
Criticality:	4.500
Weighted Operability Value:	236.25
Weighted Deficit Value:	213.75

NTDS Operator

Task: 2.1 Collect and enter EW data into NTDS
Subtasks
2.1.1 Enter manual ID information into NTDS

Operability Value:	9.857
Criticality:	4.500
Weighted Operability Value:	45.06
Weighted Deficit Value:	405.64

2.1.2 Enter manual ESM/NTDS track associations

Operability Value:	20.286
Criticality:	4.714
Weighted Operability Value:	95.63
Weighted Deficit Value:	375.77

2.1.3 Perform triangulation of ESM bearing lines

Operability Value:	25.000
Criticality:	4.429
Weighted Operability Value:	110.73
Weighted Deficit Value:	332.18

2.1.4 Enter EW fixes

Operability Value:	22.143
Criticality:	5.000
Weighted Operability Value:	110.72
Weighted Deficit Value:	389.29

2.1.5 Advise operators of bearing resolution

Operability Value:	23.714
Criticality:	4.429
Weighted Operability Value:	105.03
Weighted Deficit Value:	337.87

2.1.6 Evaluate externally reported ESM bearings

Operability Value:	57.143
Criticality:	4.286
Weighted Operability Value:	244.91
Weighted Deficit Value:	183.69

Task: 2.2 Report/Disseminate EW Information
Subtask
2.2.1 Report evaluated EW information

Operability Value:	34.714
Criticality:	4.571
Weighted Operability Value:	158.68
Weighted Deficit Value:	298.42

2.2.2 Update status board near console

Operability Value:	51.714
Criticality:	3.571
Weighted Operability Value:	184.67
Weighted Deficit Value:	172.43

SLQ-17 Operator

Task: 3.1 Conduct ESM Search
Subtask

3.1.1 Monitor automatic correlations/associations

Operability Value:	52.000
Criticality:	4.286
Weighted Operability Value:	222.87
Weighted Deficit Value:	205.73

3.1.2 Establish operating modes of SLQ-17 (ESM)

Operability Value:	80.571
Criticality:	3.857
Weighted Operability Value:	310.76
Weighted Deficit Value:	74.94

3.1.3 Enter detection and response parameters (ESM/ECM)

Operability Value:	45.286
Criticality:	4.429
Weighted Operability Value:	200.57
Weighted Deficit Value:	242.33

3.1.4 Monitor environment on NTDS console

Operability Value:	88.143
Criticality:	4.000
Weighted Operability Value:	352.57
Weighted Deficit Value:	47.43

3.1.5 Evaluate displayed data

Operability Value:	46.000
Criticality:	4.571
Weighted Operability Value:	210.27
Weighted Deficit Value:	246.83

Task: 3.2 Report/Disseminate EW Information
Subtask
3.2.1 Report evaluated EW information

Operability Value:	66.429
Criticality:	4.286
Weighted Operability Value:	284.71
Weighted Deficit Value:	143.89

3.2.2 Provide ESM/ECM data to NTDS

Operability Value:	67.429
Criticality:	4.000
Weighted Operability Value:	269.72
Weighted Deficit Value:	130.28

3.2.3 Monitor entry of EW data into NTDS

Operability Value:	78.571
Criticality:	2.571
Weighted Operability Value:	202.00
Weighted Deficit Value:	55.09

3.2.4 Update status board

Operability Value:	24.857
Criticality:	3.571
Weighted Operability Value:	88.76
Weighted Deficit Value:	268.34

Task: 3.3 Counter Hostile Environment
Subtask
3.3.1 Engage targets with ECM

Operability Value:	88.857
Criticality:	4.714
Weighted Operability Value:	418.87
Weighted Deficit Value:	52.53

3.3.2 Establish ECM operating Modes

Operability Value:	71.714
Criticality:	4.571
Weighted Operability Value:	327.80
Weighted Deficit Value:	129.30

3.3.3 Assist in promulgation of ECM employment criteria

Operability Value:	82.286
Criticality:	3.333
Weighted Operability Value:	274.26
Weighted Deficit Value:	59.04

WLR-1 Operator

Task: 4.1 Conduct ESM Search
Subtasks
4.1.1 Search assigned bands

Operability Value:	3.000
Criticality:	5.000
Weighted Operability Value:	15.00
Weighted Deficit Value:	485.00

4.1.2 Analyze intercepted signals

Operability Value:	14.286
Criticality:	5.000
Weighted Operability Value:	71.43
Weighted Deficit Value:	428.57

4.1.3 Check intercepts for images/harmonics

Operability Value:	87.714
Criticality:	2.286
Weighted Operability Value:	200.51
Weighted Deficit Value:	28.09

4.1.4 Accurately DF intercepted signals

Operability Value:	11.286
Criticality:	5.000
Weighted Operability Value:	56.43
Weighted Deficit Value:	443.57

4.1.5 Assist in evaluating ECM

Operability Value:	48.571
Criticality:	2.286
Weighted Operability Value:	111.03
Weighted Deficit Value:	117.57

Task: 4.2 Report/Disseminate EW Information
Subtasks
4.2.1 Provide ESM data to NTDS

Operability Value:	3.000
Criticality:	4.714
Weighted Operability Value:	14.14
Weighted Deficit Value:	457.26

4.2.2 Report evaluated EW information

Operability Value:	7.857
Criticality:	5.000
Weighted Operability Value:	39.29
Weighted Deficit Value:	460.72

4.2.3 Update status board near position

Operability Value:	82.286
Criticality:	2.429
Weighted Operability Value:	199.87
Weighted Deficit Value:	43.03

4.2.4 Log all intercepts

Operability Value:	13.429
Criticality:	4.571
Weighted Operability Value:	61.38
Weighted Deficit Value:	395.72

Task: 4.3 EMCON
Subtasks
4.3.1 Monitor EMCON

Operability Value:	46.429
Criticality:	4.286
Weighted Operability Value:	198.99
Weighted Deficit Value:	229.61

4.3.2 Report violations of EMCON

Operability Value:	44.143
Criticality:	3.857
Weighted Operability Value:	170.26
Weighted Deficit Value:	215.44

4.3.3 Log violations of EMCON

Operability Value:	49.286
Criticality:	3.000
Weighted Operability Value:	147.86
Weighted Deficit Value:	152.14

4.3.4 Monitor MUTE

Operability Value:	35.571
Criticality:	3.714
Weighted Operability Value:	132.11
Weighted Deficit Value:	239.29

EW Status Board

Task: 5.1 Maintain Status Boards
Subtasks
5.1.1 Communicate with operators

Operability Value:	10.573
Criticality:	4.571
Weighted Operability Value:	48.33
Weighted Deficit Value:	408.77

5.1.2 Advise operators of any information received

Operability Value:	24.429
Criticality:	4.000
Weighted Operability Value:	97.72
Weighted Deficit Value:	302.28

5.1.3 Update status boards

Operability Value:	20.289
Criticality:	4.714
Weighted Operability Value:	95.64
Weighted Deficit Value::	375.76

APPENDIX C

THE DELTA METHOD

This appendix gives a brief description of the delta method, an algorithm for converting ordinal measures on the cells of a matrix to a scale with interval properties satisfying the conditions of additive conjoint measurement. This appendix is essentially the same as that in Ref. 2, only being changed to reflect the present application. For a further and fuller description, see Coombs [Ref. 6]. The method will be briefly described using the matrix in Figure C-1. This matrix is similar in form to the 4x4 matrix used in the OW/SE rating matrix developed for the Subtask Questionnaire but smaller in size.

Factor II		A	B	C
	R	6	8	9
	Q	3	4	7
	P	1	2	5

Factor I

Figure C-1

In Figure C-1, Factors I and II represent two independent measures, and the numbers in the cells of the matrix represent an empirical ordering of overall performance over combinations of factors I and II. Higher numbers represent better overall performance.

The resulting scales will be interval measures of I and II as well as overall performance. Because the scale is additive, the measure of overall performance of any cell must be the sum of the corresponding row and column scale values. Furthermore, the resulting performance measure must reflect the ordering of the cells of the matrix. Consequently, any set of scale values which provide an additive representation for a matrix must simultaneously satisfy the equations implied by the additive representation and the inequalities specified by the rank ordering of the cells of the matrix. Conditions under which a set of linear equations and inequalities have a common solution are specified mathematically by the Theorem of the Alternative. In practice, solutions may be found by using various linear programming techniques. The delta method is one such technique that is simple enough to be done by hand for small matrices.

The delta method proceeds, in general, as follows. Cells in the matrix are initially given arbitrary positive scale values (represented by the Greek letter, delta; hence, the name)(we will replace delta with the Roman letter d, for

ease of computation) which satisfy the equations specified by the additive representation. For example, if B were assigned the value d_1 and Q were assigned the value d_3, then the cell BQ would have the value $d_1 + d_3$. After initial assignments are made, the relationships between scale values and the d's are changed to take into account the constraints given by the rank ordering of the matrix. When the procedure is completed and a solution is found, scale values are represented by positive linear combinations of the d's, such that any choice of positive d's will lead to scale values which satisfy both the equations implied by additivity and the inequalities implied by rank order.

The levels of each factor are assigned values which reflect the ordering on that factor. Thus for Factor I, A will be assigned a value of 0 since it is the lowest level of the factor. B will be assigned an arbitrary positive value of d_1. Since C is a higher level of performance than B, it may be expressed as $d_1 + d_2$ where d_2 is an arbitrary positive constant representing the difference between the scale values of B and C. Similarly, in Factor II, P, Q, and R may be assigned values of 0, d_3, and d_4, respectively. Since the overall performance is an additive combination of the two factors, the scale value of individual cells may be stated in terms of the d's as has been done in Figure C-2.

	d_3+d_4 R	d_3+d_4	$d_1+d_3+d_4$	$d_1+d_2+d_3+d_4$
Factor II	d_3 Q	d_3	d_1+d_3	$d_1+d_2+d_3$
	O P	O	d_1	d_1+d_2
		A	B	C
		O	d_1	d_1+d_2

Factor I

Figure C-2

Alternately, the scale values may be displayed as in Figure C-3. this figure represents the work sheet which will be used in the algorithm. On the top half of the figure are the individual factor scale values. On the bottom half are the values of overall performance, listed in decreasing rank order. The columns represent the four d's. the numbers in the work sheet are the coefficients in the equation:

Scale Value = $coef_1 \times d_1 + coef_2 \times d_2 + coef_3 \times d_3 + coef_4 \times d_4$.

A blank indicates a coefficient of zero.

	d_1	d_2	d_3	d_4			
A							
B	1						
C	1	1					
P							
Q			1				
R			1	1			
CR	1	1	1	1			
BR	1		1	1			
CQ	1	1	1				
AR			1	1			
CP	1	1					
BQ	1		1				
AQ			1				
BP	1						
AP							

Figure C-3

The general procedure involves comparing cells adjacent in the rank ordering of the matrix and redefining the relationship between the scale values and the d's so that the order of the cells will be preserved for any choice of positive d's. the cells may be examined in any order; in this example and the Layout Effectiveness application, we will start from the lowest performance and proceed to the highest level. This involves moving from the bottom to the top of the work sheet.

The first pair of cells in BP and AP. examination of Figure C-3 shows that BP is higher than AP. Since BP has

value d_1 and AP has value 0, it may be concluded that $d_1 > 0$. This inequality is clearly satisfied for any positive value for d_1, so it is not necessary to redefine this value. It will be recalled that values were assigned to A and B so that B would have a higher value than A.

The second inequality is AQ > BP. Substituting the values in this inequality gives $d_3 > d_1$. This inequality is not true for all values of d_3 and d_1. However, since $d_3 > d_1$, it possible to replace d_3 by $d_1 + d_3'$, for positive d_3'. Now, for any choice of positive d_1 and d_3', the inequality $d_1 + d_3' > d_1$ holds. On the work sheet, d_3 is replaced by $d_1 + d_3'$; that is, in any row with a d_3, a d_1 and a d_3' are added and the d_3 is deleted. For convenience, and because the d_3' column looks exactly like the d_3 column, the d_3' column is put where d_3 was. This is merely a relabeling of columns. Note that as many 'marks' as were in the d_3 column are added to the d_1 column. The work sheet at this point looks like Figure C-4.

The next inequality, BQ > AQ implies $2d_1 + d_3' > d_1 + d_3'$ or $d_1 > 0$. Again it is not necessary to make any changes to satisfy this constant.

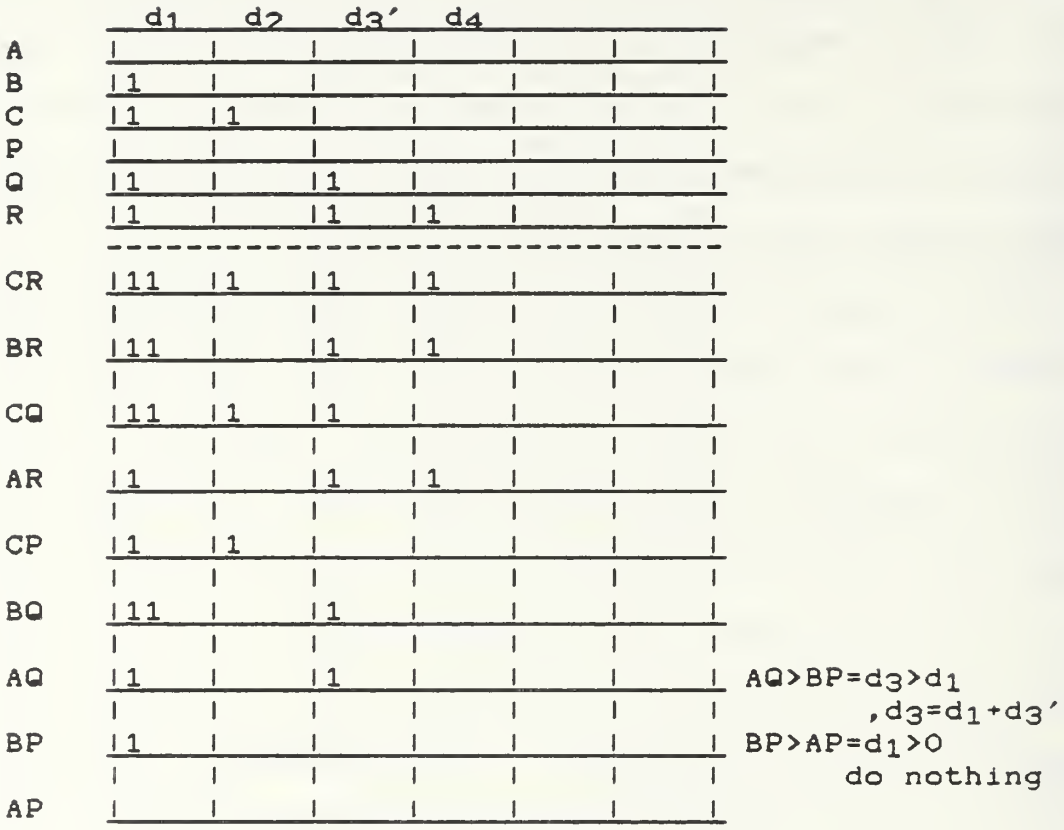


Figure C-4

Proceeding up the work sheet, the next inequality is CP > BQ. This implies that $d_2 > d_1 + d_3'$. Here, we do the same as before, in that we redefine d_2 as $d_1 + d_3' + d_2'$, and consequently replacing d_2 in every row in which it occurs by a d_1, d_3', and d_2'. Again d_2' is put in the column where d_2 was. Consequently, the procedure involves relabeling the d_2 column d_2' and adding a d_1 and a d_3' for each d_2 in any row in which a d_2 appears. The work sheet at this point looks like Figure C-5.

	d_1	d_2'	d_3'	d_4			
A							
B	1						
C	11	1	1				
P							
Q	1		1				
R	1		1	1			
CR	111	1	11	1			
BR	11		1	1			
CQ	111	1	11				
AR	1		1	1			
CP	11	1	1				
BQ	11		1				
AQ	1		1				
BP	1						
AP							

$CP > BQ = d_2 > d_1 + d_3'$
$d_2 = d_1 + d_3' + d_2'$
$BQ > AQ = d_1 > 0$
do nothing.
$AQ > BP = d_3 > d_1$
$d_3 = d_1 + d_3'$
$BP > AP = d_1 > 0$
do nothing.

Figure C-5

The inequality AR > CP implies a similar inequality among d's and is handled the same way. The work sheet at this point is given in Figure C-6.

The ordering of CQ > AR implies an inequality among the d's which is handled somewhat differently from the previous inequalities. CQ > AR implies that $d_1 + d_3' > d_4'$. Since there are two d's on the left side of the inequality, it is not possible simply to make the substitution:

$$d_1 + d_3' = d_4' + d_1' + d_3''.$$

Some rows may have different numbers of d_1 and d_3', so this replacement rule would be impossible to implement.

The following three step method is used to redefine the d's. First, d_4' is split into two parts, d_4'' and d_5. Since $d_1 + d_3' > d_4'$, this division may be arbitrarily done so that $d_1 > d_4''$ and $d_3' > d_5$. The preceding two inequalities may be handled by

	d_1	d_2'	d_3'	d_4'			
A							
B	1						
C	11	1	1				
P							
Q	1		1				
R	11	1	1	1			
CR	1111	11	11	1			
BR	111	1	1	1			
CQ	111	1	11				
AR	11	1	1	1			
CP	11	1	1				
BQ	11		1				
AQ	1		1				
BP	1						
AP							

AR>CP=d_4>d_1+d_2'
d_4=d_1+d_2'+d_4'
CP>BQ=d_2>d_1+d_3'
d_2=d_1+d_3'+d_2'
BQ>AQ=d_1>0
do nothing.
AQ>BP=d_3>d_1
d_3=d_1+d_3'
BP>AP=d_1>0
do nothing.

Figure C-6

previously discussed methods. Thus the three replacements are :

$d_4' = d_4'' + d_5$,

$d_1 = d_4'' + d_1'$, and

$d_3' = d_3'' + d_5$.

Now for any choice of positive d's, CQ > AR is satisfied. The work sheet now looks like Figure C-7.

The methods of handling the remaining inequalities have already been discussed. Note that the steps to complete the worksheet is (matrix size - 1), or in the example, 8. For the Module Operability application there were 15 steps.

When completed, the top half of the work sheet shows the relationship between scale values and the newly defined d's. For the example given, the following relationships hold:

$A = 0$
$B = d_1' + d_3'' + d_4'''$
$C = 2d_1' + d_2' + 3d_3'' + 2d_4''' + d_5$
$P = 0$
$Q = d_1' + 2d_3'' + d_4''' + d_5$
$R = 2d_1' + d_2' + 4d_3'' + 3d_4''' + 2d_5$

	d_1	d_2'	d_3'	d_4'	d_5		
A							
B	1						
C	11	1	1	11	1		
P							
Q	1		1	1	1		
R	11	1	1	111	11		
CR	1111	11	11	11	5	111	
BR	111	1	1	1111	11		
CQ	111	1	11	111	11		
AR	11	1	1	111	11		
CP	11	1	1	11	1		
BQ	11		1	11	1		
AQ	1		1	1	1		
BP	1			1			
AP							

$\{d_4' = d_4'' + d_5$
$\{d_1 = d_4'' + d_1'$
$CQ > AR = d_1 + d_3' > d_4'$
$\{d_3' = d_5 + d_3''$
$AR > CP = d_4 > d_1 + d_2'$
$d_4 = d_1 + d_2' + d_4'$
$CP > BQ = d_2 > d_1 + d_3'$
$d_2 = d_1 + d_3' + d_2'$
$BQ > AQ = d_1 > 0$
do nothing.
$AQ > BP = d_3 > d_1$
$d_3 = d_1 + d_3'$
$BP > AP = d_1 > 0$
do nothing.

Figure C-7

Any choice of positive d's will give a scale for Factors I and II as well as overall performance which is an additive representation, and in which the overall ordering agrees with the empirical ordering. Figure C-8 contains the results of this example.

	d_1'	d_2'	d_3''	d_4'''	d_5	d_6	d_7	d_8		
A									=	0
B	1		1	1					=	3
C	11	1	111	11	1				=	9
P									=	0
Q	1		11	1	1				=	5
R	11	1	1111	111	11				=	12
CR	1111	11	7	1111	111				=	20
BR	111	1	5	1111	11				=	15
CQ	111	1	5	111	11				=	14
AR	11	1	1111	111	11				=	12
CP	11	1	111	11	1				=	9
BQ	11		111	11	1				=	8
AQ	1		11	1	1				=	5
BP	1		1	1					=	3
AP									=	0

Figure C-8

A common choice of d's is to make them all equal to 1. This choice for d yields a set of scale values which represent the set of minimal integers which will produce the requires rank order of the matrix cells.

The completed work sheet for the Module Operability application follows. Note that the numbers within the d's are expressed in arabic numerals for viewing ease and the totals are listed on the side.

	d_1'''	d_2''''	d_3'	d_4''	d_5'''	d_6'''	d_7	d_8	
A	1	1	1	1	1	1	1	1	= 0
B	2	3	4	3	3	1	4	2	= 22
C	3	5	7	5	4	2	6	3	= 35
D	4	6	10	7	6	2	8	4	= 47
P	1	1	1	1	1	1	1	1	= 0
Q	2	3	5	4	3	1	4	2	= 24
R	3	5	8	6	5	2	7	4	= 40
S	5	7	11	8	7	3	9	5	= 55
SD	9	13	21	15	13	5	17	9	=102
SC	8	12	18	13	11	5	15	8	= 90
RD	7	11	18	13	11	4	15	8	= 87
SB	7	10	15	11	10	4	13	7	= 77
RC	6	10	15	11	9	4	13	7	= 75
QD	6	9	15	11	9	3	12	6	= 71
RB	5	8	12	9	8	3	11	6	= 62
QC	5	8	12	9	7	3	10	5	= 59
SA	5	7	11	8	7	3	9	5	= 55
PD	4	6	10	7	6	2	8	4	= 47
QB	4	6	9	7	6	2	8	4	= 46
RA	3	5	8	6	5	2	7	4	= 40
PC	3	5	7	5	4	2	6	3	= 35
QA	2	3	5	4	3	1	4	2	= 24
PB	2	3	4	3	3	1	4	2	= 22
PA	1	1	1	1	1	1	1	1	= 0

Figure C-9

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